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"RIBBON ROCK," AN UNUSUAL BERYLLIUM-BEARING TACTITE.[1]

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ABSTRACT.

The beryllium deposits at Iron Mountain, near the northern end of the Sierra Cuchillo in Sierra and Socorro Counties, New Mexico, are unusual products of contact metamorphism. They occur in irregular bodies of tactite formed by replacement of Paleozoic limestone, generally at or near contacts with small intrusive masses of rhyolite, aplite, and fine-grained granite. The metamorphism took place in mid-Tertiary time. Beryllium is present chiefly in the complex silicate minerals helvite and danalite, and is a minor constituent of the garnet grossularite, a boron-bearing idocrase, and chlorite. These minerals are known to occur in noteworthy concentrations in only one type of rock, a peculiar rhythmically layered variety of tactite to which the name "ribbon rock" is given.

The structure of such tactite is very conspicuous, and appears in section as thin, finely crenulated bands of magnetite alternating with similar bands of silicate minerals and finely crystalline fluorite. Concentric banding about fluorite-rich pod-like masses is common. Bodies of "ribbon rock" range in size from inch-thick lenses to large masses amounting to thousands of tons; most appear to have been formed along contacts between recrystallized limestone and massive magnetite-andradite tactite, chiefly by replacing fluids penetrating the limestone from fractures. The layered structure is interpreted as a diffusion effect.

The formation of massive and "ribbon rock" tactites can be traced through a range of falling temperature from a stage

[1] Published with the permission of the Director, Geological Survey, U. S. Department of the Interior.

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characterized by deposition from iron-rich vapors to a stage in which hydrothermal solutions were dominant. Both vapors and liquids appear to have been acid. Reducing conditions undoubtedly existed during the latter part of the hydrothermal stage. The occurrence of beryllium in "ribbon rock," but not in typical massive tactite, may signify that its compounds in deposits at or near intrusive contacts are confined to rocks of hydrothermal origin. The occurrence of "ribbon rock" is suggested as a potentially useful clue for recognition of beryllium-bearing contact deposits elsewhere; at least two other occurrences of what apparently is "ribbon rock" have been described in the literature.

INTRODUCTION.

THE remarkable pyrometasomatic deposits in the Iron Mountain district, New Mexico, have from time to time drawn the attention of engineers and prospectors seeking workable concentrations of iron, gold, and base metals. Though briefly described by several geologists,[2] they caused little widespread interest until November, 1941, when L. W. Strock[3] suggested them as possible sources of beryllium. This new interest was quickened in June, 1942, when T. C. Parker, principal claim holder in the area, discovered several promising occurrences of tungsten ore.

The Geological Survey and the Bureau of Mines have been engaged in detailed examination and exploration of the deposits since May, 1942, and these investigations, which are not yet complete, have yielded critical information concerning a most unusual type of beryllium-bearing rock. Not only is this rock unusual in appearance, composition, and origin, but it contains all the noteworthy concentrations of beryllium known in the district at the present time; thus, it may well be a useful clue for recognition of similar beryllium occurrences elsewhere. The economic significance of this rock, as well as the interesting scientific problems

[2] Smythe, D. D.: A contact metamorphic iron-ore deposit near Fairview, New Mexico. ECON. GEOL. 16: 410–418, 1921; Lasky, S. G.: The ore deposits of Socorro County, New Mexico. New Mexico School of Mines, State Bur. of Mines and Min. Res., Bull. 8: 138–139, 1932; Harley, G. T.: The geology and ore deposits of Sierra County, New Mexico. New Mexico School of Mines, State Bur. of Mines and Min. Res., Bull. 10: 118, 1934.

[3] Strock, L. W.: A new helvite locality—a possible beryllium deposit. ECON. GEOL. 36: 748–751, 1941.

that it introduces are thought to justify the descriptions and comments that follow.

Iron Mountain lies near the northern end of the Sierra Cuchillo in Sierra and Socorro Counties, New Mexico, and can be reached

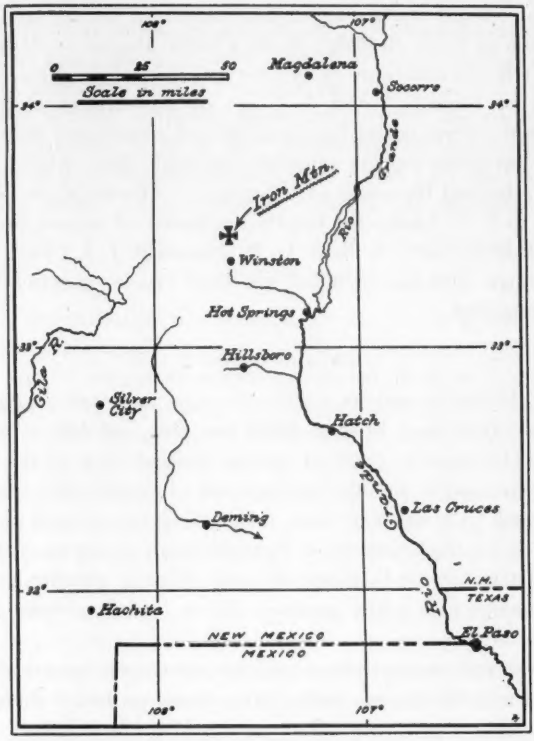


FIG. 1. Index map of southwestern New Mexico, showing location of Iron Mountain.

from Winston (formerly Fairview) and Hot Springs (Fig. 1) by automobile over fair gravel roads. Brown City, a group of tents and semi-permanent structures, is situated at the west base of the mountain ten miles north of Winston.

ACKNOWLEDGMENTS.

T. C. Parker, who had devoted many months to a thorough prospecting of all promising parts of the district prior to the writer's arrival, was most generous with all information at his disposal. Field work was further facilitated by the active cooperation of F. A. Rutledge of the Federal Bureau of Mines and by the efficient assistance of W. Porter Irwin of the New Mexico School of Mines. Jewell J. Glass, of the Geological Survey, furnished several useful thin sections and contributed many data on the beryllium-bearing minerals, although their detailed treatment is beyond the scope of this paper. The writer is also indebted to S. G. Lasky for helpful discussion of several problems in the field and to C. S. Ross, G. R. Mansfield, J. J. Glass, H. M. Bannerman, and Ian Campbell for their critical examination of the manuscript.

GENERAL GEOLOGY.

Iron Mountain and its northerly extension form a ridge-like mass two miles long, 1,000 to 3,000 feet wide, and 300 to 700 feet high. This mass is a narrow, eastward-tilted block of the basin-range type, and is bounded on both sides by faults that converge northward. On its steep slopes and more gentle summit portions is exposed a thick section of Pennsylvanian limestone (Magdalena), intricately cut by plugs, sills, and dikes of rhyolite, porphyritic rhyolite, and aplitic granite. These intrusive rocks are of probable Miocene age.

Widespread metamorphism and metasomatism, genetically associated with the igneous rocks, have caused profound changes in the appearance and composition of the Magdalena beds. Metamorphism in the more mildly affected parts of the area has caused recrystallization of the limestone and the formation of hornfels from the more shaly beds. Metasomatism, representing the more severe contact effects, has resulted in silication of certain susceptible parts of the formation. Two types of silicate rock, clearly differentiable on the basis of their iron content, are present; they

correspond to the zones of light- and dark-colored silicates as defined by Hess and Larsen.[4]

Dense, light-gray to greenish-gray quartz-pyroxene-clinozoisite-plagioclase granulites of varying mineral proportions are the chief iron-poor silicate rocks, and in general were formed from the less pure portions of the calcareous section. They can be traced along the strike into unreplaced beds through transition zones measurable in hundreds of feet, but contacts paralleling the strike tend to be rather abrupt. Irregular bodies of iron-rich silicate rock, or tactite,[5] generally lie at or near the borders of igneous masses; they are in part contemporaneous with and in part later than the granulite beds. Tactite-granulite contacts are characteristically sharp.

MASSIVE TACTITE.

Two distinctly different varieties of tactite are present in the Iron Mountain area; the more common of these is a typical massively bedded magnetite-andradite rock of black to greenish or brownish color. Hedenbergite and hematite occur in local abundance, and fluorite, apatite, diopside, iron-rich amphibole, quartz, feldspar, spinels, idocrase, biotite, chlorite, scheelite, powellite, willemite, and sulphides of iron and the base metals are later-stage minor constituents (see Table I). The rock plainly has been formed through replacement of recrystallized limestone and to a lesser extent at the expense of iron-poor silicate rocks. Such replacement bodies range in size from inch-thick lenses to great masses amounting to millions of tons; the largest of these lie along the summit and high on the east and west slopes of the Iron Mountain block. Despite many complexities of detail, they are generally tabular and conform very crudely to the bedding of the adjacent sedimentary rock. They do not everywhere lie against the igneous intrusions, but may be separated from them by a few

[4] Hess, F. L., and Larsen, E. S.: Contact-metamorphic tungsten deposits in the United States. U. S. Geol. Surv. Bull. 725–D: 252–253, 1921.

[5] Hess, F. L.: Tactite, the product of contact metamorphism. Amer. Jour. Sci., 4th ser. 48: 377–378, 1919; Hess, F. L., and Larsen, E. S.: U. S. Geol. Surv. Bull. 725–D: 249, 1921.

TABLE 1.

MODAL COMPOSITION OF MASSIVE TACTITE FROM IRON MOUNTAIN, NEW MEXICO.*

	1	2	3	4	5
Magnetite	91	73	19	28	16
Hematite	Tr	1	6	7	9
Andradite	8	16	4	54	4
Hedenbergite	—	Tr	45	—	—
Diopside	—	3	—	—	—
Amphibole	—	—	3	—	—
Feldspar	Tr	1	13	Tr	—
Fluorite	Tr	2	2	4	52
Quartz	—	1	1	Tr	1
Apatite	—	—	Tr	—	Tr
Spinels	—	—	Tr	—	1
Idocrase	—	—	—	—	6
Biotite	—	Tr	—	—	Tr
Chlorite	—	—	Tr	—	4
Scheelite and powellite	—	—	1	2	3
Willemite	—	—	Tr	1	1
Pyrrhotite	Tr	1	Tr	—	—
Alteration products, chiefly limonite	Tr	1	5	3	2

1—Specimen of simple massive tactite, summit of North Peak. 2—Composite chip sample, Old Adit body, Discovery Gulch. 3—Composite chip sample, northeast slope of North Peak. 4—Systematic five-foot channel sample, Upper Star body, North End area. 5—Specimen of highly mineralized tactite, west slope of North Peak.

Nos. 1 and 2 are most nearly representative of the massive tactite as a whole.

* Each mode determined microscopically by the counting of 1,000 grains of representative crushed material.

feet or tens of feet of relatively less metamorphosed sedimentary beds. Masses of tactite that flank concordant igneous bodies are much more continuous than those adjacent to cross-cutting contacts, which tend to feather out along favorable beds and hence are extremely irregular in pattern.

Contacts between massive tactite and other rocks are sharp. That the tactite postdates recrystallized limestone and much of the granulite is demonstrated by the fact that it cross-cuts and invades both of these rocks and encloses remnants of them. Such relations can be seen wherever contacts or irregular contact zones are exposed. Evidently the brittle tactite was repeatedly broken and sheared during the later stages of its formation, each fracture or other opening being promptly "healed" by magnetite, andradite, or other minerals. The resultant rock consists of garnet and magnetite with many thin laminæ and lenses of later minerals,

chiefly additional magnetite and andradite with some scheelite and powellite. It is tough and massive where no post-mineral shearing has occurred. A still later period of mineralization is represented by fluorite-rich shear and breccia zones in which beryllium, manganese, and zinc minerals are locally abundant.

The other variety of tactite is a remarkable product of hydrothermal action, and is treated in detail in the following paragraphs.

"RIBBON ROCK" TACTITE.

General Description. The "ribbon rock" variety of Iron Mountain tactite is named for the layered structure that at once distinguishes it from the massive tactite just described. It consists typically of thin, continuous, minutely crenulated layers or shells, each contrasting mineralogically with the layers immediately adjacent. In section the layers appear as wavy ribbons 0.05 mm. to 3 mm. wide, with a probable average of about 0.2 mm.; most seemingly broader ribbons are found upon close inspection to be themselves finely banded. Many of the layers are arranged concentrically about spherical to irregularly ellipsoidal crystalline pods, and are progressively thicker toward the pods. Other layers appear to be nearly flat sheets or gently curving shells, and can be traced for distances as great as six inches before becoming involved in zones of intricate convolutions that surround groups of pods and their associated concentric shells. Typical masses of "ribbon rock" are shown in Figs. 2 and 3.

A strikingly similar ribboned tactite from the Seward Peninsula, Alaska, has been attributed to "orbicular contact metamorphism" by Knopf,[6] who describes it as follows:

> The orbules are composed of an alternating succession of concentric black and white bands, commonly a millimeter or so in breadth. . . . Many of the sections through the orbules are perfect circles, a maximum diameter of 8 inches being noted, but elliptical forms, due to the inter-

[6] Knopf, Adolph: Geology of the Seward Peninsula tin deposits. U. S. Geol. Surv. Bull. 358: 45–46, pl. IV, 1908; See also Steidtmann, Edward, and Cathcart, S. H.: Geology of the York tin deposits, Alaska. U. S. Geol. Surv. Bull. 733: 73–76, pl. IX, 1922.

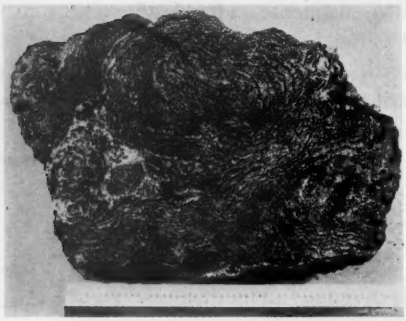


FIG. 2. Weathered surface of magnetite-rich "ribbon rock" from West Slope area, Iron Mountain. Dark layers of magnetite alternate with layers of crystalline fluorite and minor amounts of helvite and quartz.

FIG. 3. Sawn slab of typical silicate-rich "ribbon rock," North End area, Iron Mountain. Light-colored ribbons, veinlets, and irregular masses are aggregates of crystalline fluorite and silicate minerals.

ference of contiguous orbules, are common. . . . Where several small independent orbules have formed around closely spaced centers highly intricate structure resembling that of contorted gneiss has been evolved.

Another occurrence of what is probably typical "ribbon rock" tactite has been described from Pitkäranta, Finland, by Trüstedt.[7]

Mineralogy. The Iron Mountain "ribbon rock" is essentially a garnet-poor magnetite-fluorite tactite. Layers of magnetite and local intimately associated hematite commonly alternate with somewhat thinner layers composed of crystalline fluorite, silicate minerals, or fluorite-silicate mineral aggregates. Two distinctive varieties of "ribbon rock" occur in the district; they differ chiefly in the mineral composition of their magnetite-free layers.

A dark, beryllium-rich variety forms small bodies in Discovery Gulch, a narrow canyon immediately east of Brown City, as well as on the west slope of the mountain about 1,500 feet northeast of Brown City. Its wavy magnetite laminæ are 0.2 mm. to 10 mm. thick, with much thinner intervening layer-aggregates of fluorite, helvite, and locally quartz (Fig. 2). Irregular masses of adularia occur in the less strongly layered parts of the rock. Limonite, kaolinite, manganese oxides, and other alteration products are locally abundant; an appreciable part of the limonite and manganese oxides has been formed from near-surface oxidation of the helvite, a complex silicate-sulphide mineral that contains beryllium, iron, manganese, and zinc. It occurs as rutile-red to amber-colored crystals and crystalline aggregates, and has been overlooked in times past because of its exceedingly close resemblance to garnet.[8] The detailed and distinguishing properties of this interesting mineral species have been described elsewhere,[9] and so will not be repeated here. So far as can be determined,

[7] Trüstedt, O.: Die erzlagerstätten von Pitkäranta am Ladoga-See. Bull. Comm. Geol. de Finlande, No. 19: 226, 1907.

[8] See, for example, Smythe, D. D.: A contact metamorphic iron-ore deposit near Fairview, New Mexico. Econ. Geol. 16: 414, 1921.

[9] Strock, L. W.: A new helvite locality—a possible beryllium deposit. Econ. Geol. 36: 748–751, 1941; Jahns, R. H., and Glass, J. J.: Beryllium occurrence near Winston, New Mexico. U. S. Geol. Surv. Memo. for the press, Nov. 7, 1942; Glass, J. J., Jahns, R. H., and Stevens, R. E.: Helvite and danalite from New Mexico and the helvite group. Amer. Mineralogist, in press, 1943.

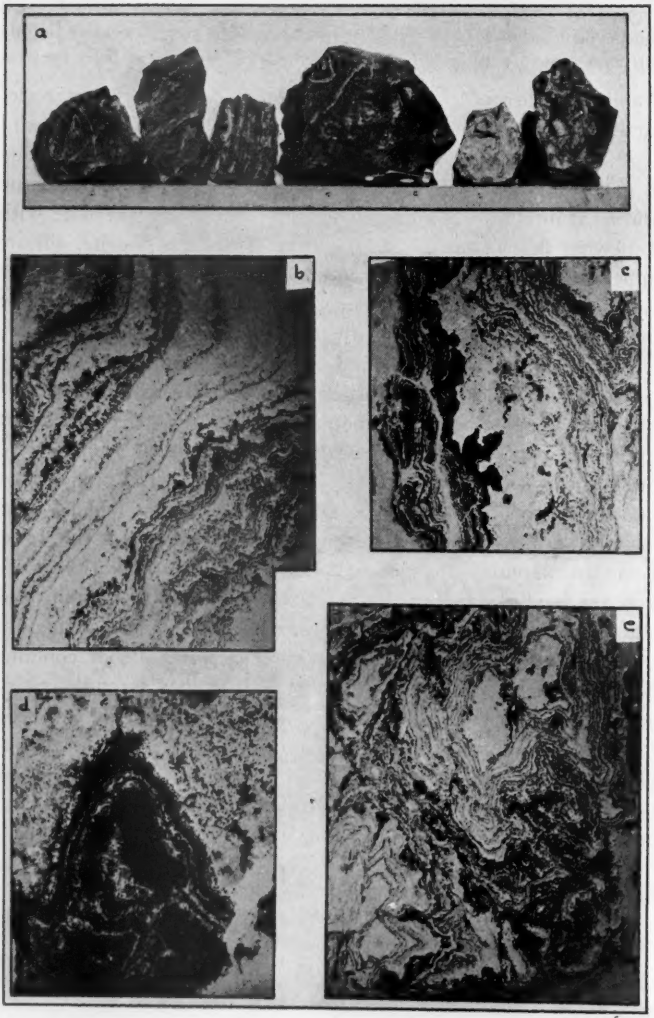


FIG. 4.

garnet is absent from the magnetite-rich variety of "ribbon rock." The mineral compositions of several samples and typical specimens are given in Table 2.

TABLE 2.

MODAL COMPOSITION OF MAGNETITE-RICH "RIBBON ROCK" FROM IRON MOUNTAIN, NEW MEXICO.*

	1	2	3	4	5
Magnetite	68	39	42	28	47
Fluorite	16	41	25	30	37
Helvite	11	5	14	24	2
Adularia	—	—	9	5	3
Quartz	3	—	2	4	—
Biotite and chlorite	—	4	—	—	3
Alteration products (limonite, kaolinite, etc.)	2	11	8	9	8

1—Systematic grid samples from area of 11 square feet, Hot Spot body, Discovery Gulch. 2—Systematic grid sample from area of 14 square feet, Hot Spot Extension body, Discovery Gulch. 3—Systematic two-foot channel sample from Jackpot No. 2 body, 1,500 feet northeast of Brown City. 4—Specimen of high-grade beryllium ore, Hot Spot body, Discovery Gulch. 5—Specimen of low-grade beryllium ore, Jackpot No. 2 body, 1,500 feet northeast of Brown City.

* Each mode determined microscopically by the counting of 1,000 grains of representative crushed material.

The predominance of dark-colored constituents causes most of the layered structure to be indistinct on freshly broken faces, though it is readily recognizable on most weathered surfaces (Fig. 2). The layers are unusually thick in this type of "ribbon rock," but crystalline pods are not common; where they do occur, they consist chiefly of helvite and fluorite, and may reach thicknesses of an inch or more. Small vugs lined with drusy fluorite, helvite, and low-temperature quartz have also been observed.

FIG. 4. Silicate-rich "ribbon rock" from Iron Mountain, New Mexico. a. Typical hand specimens, North End area. ×0.1. b. Section of regularly ribboned tactite, Beryllium Reef body. Narrow elongated black masses at upper left are scales of specular hematite. ×2.8. c. Orbicular tactite, Beryllium Queen body. Cracks in lower left are breaks in thin section. ×2.8. d. Section through orbicular pod in biotite-rich "ribbon rock" from lower Discovery Gulch. ×2.3. e. Section of typical pod-rich "ribbon rock," Beryllium Chief body. ×2.8. In all sections the black material is magnetite with minor hematite; the white to light gray is fluorite; and the gray comprises silicate minerals.

Photographs b and c by L. A. Wilke.

The other, more typical variety of "ribbon rock" contains less magnetite and consequently is lighter in color (Figs. 3, 4); ordinarily it occurs as much larger masses of somewhat wider distribution. Many of its thin magnetite layers include intimately associated hematite (Fig. 4), and in some places near crystalline lenses and pods they give way entirely to layers of specularite. The light-colored minerals, which combine with the iron oxides to give the rock a greenish tan to rusty brown appearance, are chiefly colorless to greenish fluorite, green biotite and chlorite, and a pale, yellowish green prismatic idocrase. Minor constituents are honey-yellow grossularite, unusual varieties of helvite and danalite that are hardly distinguishable from the grossularite, and diopside, clinozoisite, spinels, quartz, adularia, graphite, opal, and finely divided alteration products. The results of modal determinations made on several samples and specimens appear in Table 3.

The idocrase, garnet, helvite and danalite, and at least some of the chlorite, are known to contain small quantities of beryllium, and combine to make the rock a potential large-tonnage, low-grade source of that metal. The idocrase also contains an appreciable amount of boron, and much of the "ribbon rock" biotite gives a positive test for fluorine in the open tube. All of these minerals are being studied in detail by J. J. Glass and other members of the Geological Survey, and their properties have been described elsewhere.[10]

The crystalline pods and druses, as well as the coarser of the surrounding layers, consist chiefly of fluorite with minor amounts of grossularite, helvite, quartz, and feldspar. Films of bluish white opal coat the minerals lining some of the vugs. Carbonate-zeolite veinlets that cut layers and crystalline pods alike represent a sensibly later stage of mineralization, and commonly contain graphite, carbonate and oxides of manganese, sulphides, and chalcedony.

Distribution and Structural Relations. The magnetite-rich "ribbon rock" occurs in areas of recrystallized limestone and other contact rocks as thick pods, pipe-like masses, and thin, tabular

[10] Glass, J. J., Jahns, R. H., and Stevens, R. E.: op. cit., 1943.

TABLE 3.

MODAL COMPOSITION OF TYPICAL "RIBBON ROCK" TACTITE FROM IRON MOUNTAIN, NEW MEXICO.

	1[a]	2[a]	3[a]	4[b]	5[b]	6[b]	7[b]	8[b]	9[b]	10[c]	11[c]	12[c]
Magnetite	32	30	23	41	82	32	80	62	57	66.67[d]	57.30[d]	72.73[d]
Helvite and danalite	1	1	Tr	Tr	—	1	1	3	Tr	0.08	0.43	0.22
Garnet	2	Tr	4	6	—	7	1	1	4	——	5.12	0.82
Fluorite	33	22	13	25	5	34	7	14	12	12.33	8.54	6.81
Idocrase	2	11	37	2	Tr	3	—	Tr	5	——	1.70	——
Biotite	14	13	7	2	3	6	1	—	3			
Chlorite and sericite	5	15	3	4	4	2	3	10	2			
Hematite	3	Tr	5	Tr	1	7	4	3	7			
Diopside	Tr	—	—	Tr	—	—	—	1	—			
Clinozoisite	1	—	2	Tr	—	—	Tr	—	Tr			
Spinels	—	Tr	—	—	—	Tr	—	—	—			
Quartz	3	Tr	1	2	—	4	—	Tr	1	20.92	26.91	19.42
Adularia	—	2	Tr	—	Tr	Tr	—	—	Tr			
Graphite	—	Tr	2	—	—	—	—	—	—			
Sulfides	Tr	Tr	—	—	—	—	—	Tr	—			
Opal and zeolites	—	—	1	—	—	1	—	—	1			
Finely divided alteration products, etc.	4	6	2	17	4	2	3	5	7			

1—Specimen from old adit, lower Discovery Gulch. 2—Specimen from Hot Spot Extension body, Discovery Gulch. 3—Specimen from west slope of North Peak. 4—Composite chip sample, Jackpot No. 1 body, 2,300 feet north-northeast of Brown City. 5—Ribboned veinlets in recrystallized limestone, Jackpot Extension body, 2,300 feet north-northeast of Brown City. 6—Coarsely crystalline specimen, Beryllium Queen body, North End area.

7—Beryllium Reef body
8—Beryllium Reef body
9—Reef Extension body
10—Beryllium Chief body
11—Upper and Lower Star bodies
12—Beryllium King and Queen bodies

} 75- to 150-pound composite samples, North End area.

[a] Determined from thin sections.

[b] Determined microscopically by the counting of 1,000 grains of representative crushed material.

[c] Determined microscopically by J. J. Glass and R. W. Lemke by the counting of 8,000 or more grains of representative crushed material.

[d] Per cent by weight; other constituents by volume.

masses measurable in feet or tens of feet. Where appreciable elongation or finger-like projections are present, they tend to conform to the bedding of the surrounding rocks. In many places this magnetite-rich rock grades insensibly into typical, light-colored, silicate-rich "ribbon rock," but in the lower part of Discovery Gulch it passes abruptly into massive andradite-magnetite tactite.

The more widely distributed silicate-rich "ribbon rock" appears northeast of Brown City on the west slope of the mountain, as well as on the ridge summit and eastern slopes a mile north-northeast of Brown City. In the latter area are exposed the largest bodies, several of which are shown on the geologic sketch map (Fig. 5). They are rudely lenticular, trend parallel with the strike of the adjacent beds, and appear to dip eastward in approximate conformity with the beds. Representative dimensions are shown in Fig. 5. Such "ribbon rock" is sharply bounded from the massive tactite, granulite, and hornfels, but it generally grades along the strike into recrystallized limestone through transition zones several inches to several feet wide.

Wherever "ribbon rock" and massive garnet-magnetite tactite are both present, the massive tactite tends to occur between the "ribbon rock" and the nearest intrusive contact, as shown on the map (Fig. 5) and in the idealized sections (Fig. 6). Thus the "ribbon rock" commonly lies between massive tactite on one hand and recrystallized limestone or iron-poor silicate rocks on the other. Such a spatial arrangement is similar to that of most pyrometasomatic ores, which, according to Umpelby,[11] tend to occur in that part of the contact zone nearest the unreplaced limestone. Since the "ribbon rock" tactite and most contact ores are known to be late-stage products in the sequence of mineral deposition, neither the similarity of their position nor the position itself is particularly surprising.

The contact zones between limestone and "ribbon rock," though of great geologic interest, are rarely exposed. One particularly instructive outcrop, however, was found on the west edge of a small tactite body 2,350 feet north-northeast of Brown City; it demonstrates clearly the formation of "ribbon rock" at the expense of the recrystallized limestone. Five typical stages in this process are shown in Fig. 7 by sketches of specimens collected from this locality. Iron-rich solutions plainly entered the limestone along fractures (Fig. 7A), and penetrated outward from

[11] Umpelby, J. B.: The occurrence of ore on the limestone side of contact zones. Univ. Calif. Dept. Geol. Bull. 10: 25–37, 1916.

each fracture with replacement of the calcite (Fig. 7B, C). The rhythmic banding in the replacing material conforms in general to the original fractures and to the retreating faces of the calcite aggregates. Irregular, isolated carbonate masses (Fig. 7C, D),

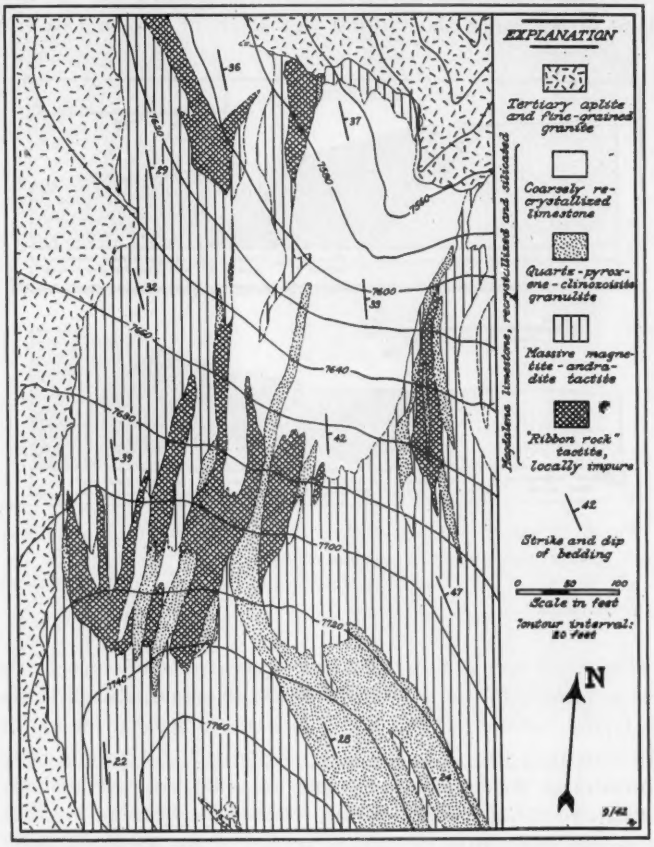


FIG. 5. Preliminary sketch map of a part of the North End area, one mile NNE of Brown City. Contacts are approximate because of poor exposures.

which represent the cores of original fracture blocks, are completely analogous in position to many of the fluorite-rich crystalline pods and druses in the end product (Figs. 4, 7E), the calcite-free "ribbon rock."

A somewhat similar series of exposures appears near the west base of the range about 6,400 feet south of Brown City. A

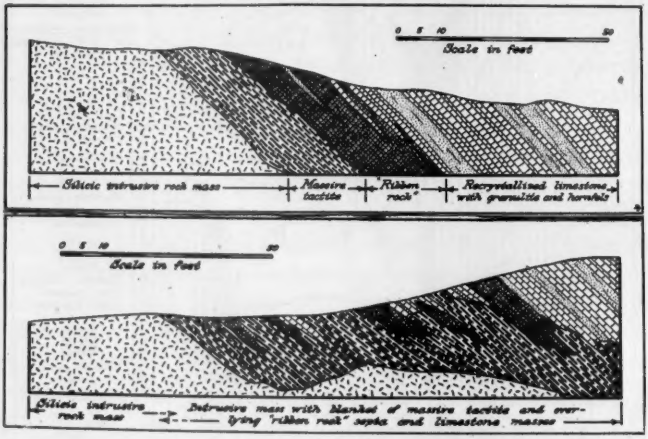

0 5 10 20
Scale in feet
Siliceic intrusive rock mass
Massive tactite
Ribbon rock
Recrystallized limestone with granulite and hornfels
0 5 10 20
Scale in feet
Siliceic intrusive rock mass
Intrusive mass with blanket of massive tactite and overlying "ribbon rock" septa and limestone masses

FIG. 6. Idealized sections showing characteristic positions of "ribbon rock" bodies with respect to igneous contacts.

a (upper). Concordant igneous contact. b (lower). Discordant igneous contact.

rather continuous 2- to 10-foot bed of massive tactite dips gently eastward beneath coarsely recrystallized limestone. Small lenses of typical "ribbon rock" appear from place to place at the top of the massive tactite, and send finger-like projections upward along fractures in the limestone. Where the solutions penerated far enough to delimit small fracture blocks, the ribboned veinlets stand out boldly from the present surface of the weathered limestone as an intricate boxwork. A few small veinlets fill fractures in the massive tactite, but are not markedly ribboned.

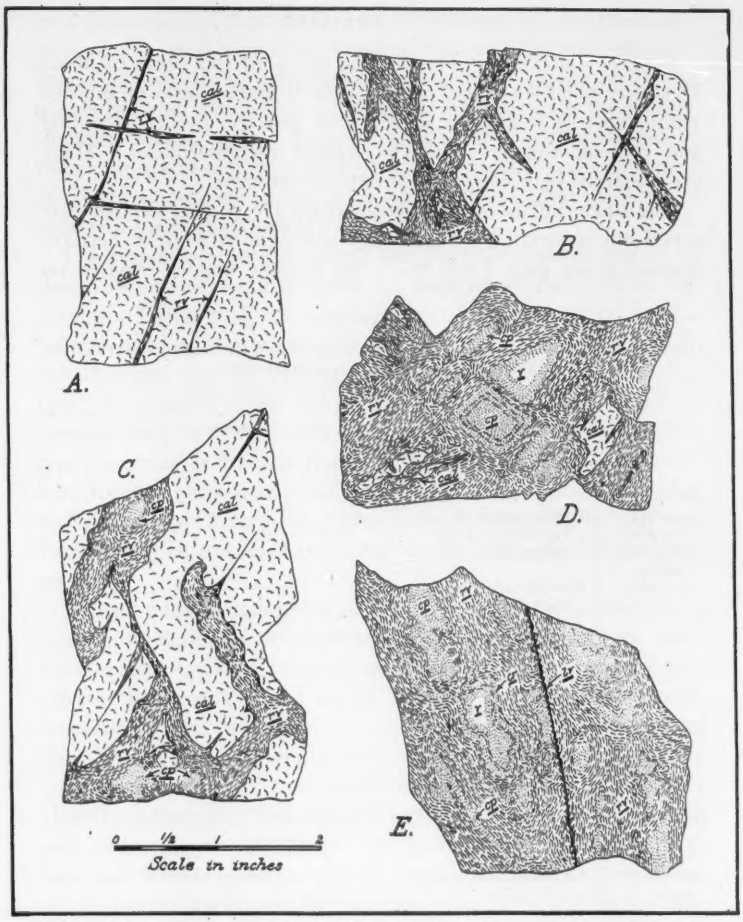


FIG. 7. Typical stages in the formation of "ribbon rock" tactite at the expense of recrystallized limestone. Each sketch made from an actual hand specimen.

cal—coarsely crystalline calcite. rv—ribboned veinlet (magnetite, hematite, fluorite, and subordinate silicate minerals). cp—crystalline pod (chiefly fluorite).v—vug (not common). cr—crystalline ribbon (fluorite and silicate minerals). lv—late-stage veinlet (quartz, calcite, zeolites, sulphides).

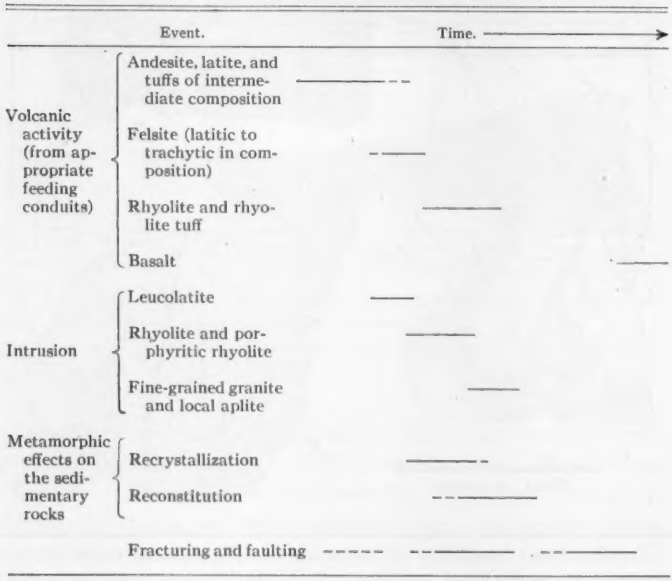
ORIGIN OF THE TACTITE.

General Statement. The detailed mapping and study of about 18 square miles south and east of Iron Mountain have established within narrow limits the sequence of geologic events preceding and contemporaneous with the contact metamorphism. These are presented here with a minimum of comment.

The silicic intrusive rocks with which the contact deposits are genetically associated are late-stage members of a great Tertiary igneous series (see Table 4). The rhyolite masses exposed on

TABLE 4.

GENERAL SEQUENCE OF IGNEOUS AND METAMORPHIC STAGES DURING THE TERTIARY PERIOD, IRON MOUNTAIN AND VICINITY.



Iron Mountain doubtless represent in part the truncated feeders of a flow-series now eroded; extensive remnants of these flows are preserved several miles to the east. The mineralogic and tex-

tural properties of the rhyolites on Iron Mountain are characteristic of a rock intermediate between an extrusive and plutonic type, and the shape, distribution, and primary structure of the masses suggest convergence at no great depth beneath the present surface. These masses were intruded during and immediately following a well-defined period of fracturing and faulting; much of the metamorphism appears to be similarly related to these structural readjustments as shown in Table 4.

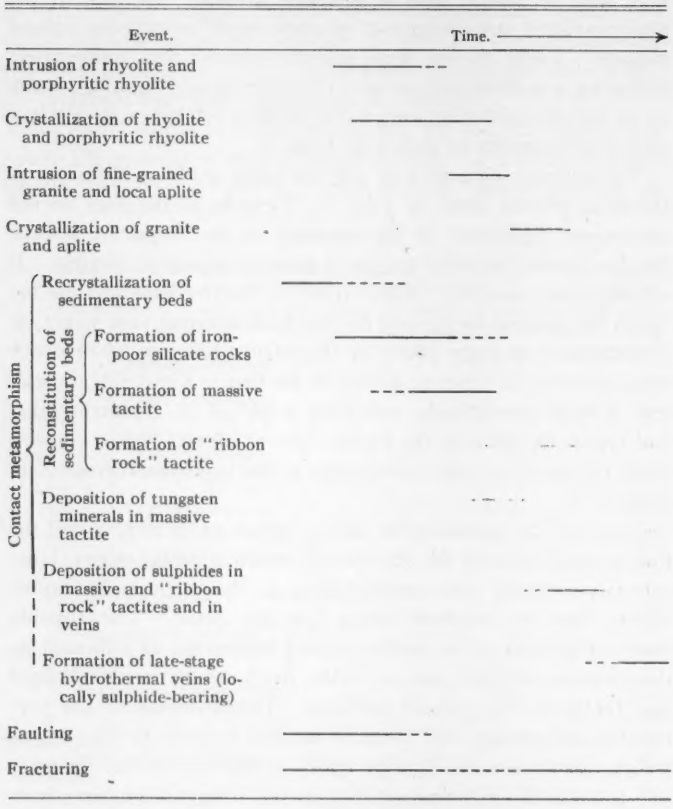
The sequence of events at any one place on Iron Mountain is shown in greater detail in Table 5. Lengths of the lines do not correspond rigorously to the duration of the respective events, but are merely intended to give a general sequential picture. It will be noted that the "ribbon rock" is intermediate in time between the massive tactite and the late hydrothermal vein stages, as demonstrated in many places by the reliable criterion of one rock type occurring as fracture fillings in another. The "ribbon rock" was formed immediately following a period of fracturing that had repeatedly affected the earlier-formed contact rocks, but was itself fractured to some extent prior to the late hydrothermal vein stage.

Many of the metamorphic effects appear to have preceded the final consolidation of the rhyolite and aplitic granite; others, however, were clearly post-consolidation, as shown by endomorphic effects that are localized along fracture zones. The rhyolite masses represent rather shallow-seated intrusions, as indicated by their texture and their role as feeders for flows that could not have lain far above the present surfaces. The thickness of the pre-rhyolite sedimentary and volcanic sections in areas to the east, as well as the known pre-rhyolite uplift of the Iron Mountain mass as a fault block (with concomitant erosion) suggest a cover whose maximum thickness probably was less than 5,000 feet at the time of contact metamorphism and rhyolite intrusion. The thickness of the cover had of course increased somewhat by the time the granite was intruded, but the hypabyssal nature of such igneous masses is none the less plain.

Temperatures of Formation. The occurrence of pyramidal

TABLE 5.

SEQUENCE OF MID-TERTIARY EVENTS AT ANY ONE PLACE IN THE IRON MOUNTAIN BLOCK.


Event.
Time.
Intrusion of rhyolite and porphyritic rhyolite
Crystallization of rhyolite and porphyritic rhyolite
Intrusion of fine-grained granite and local aplite
Crystallization of granite and aplite
Contact metamorphism
Recrystallization of sedimentary beds
Reconstitution of sedimentary beds
Formation of iron-poor silicate rocks
Formation of massive tactite
Formation of "ribbon rock" tactite
Deposition of tungsten minerals in massive tactite
Deposition of sulphides in massive and "ribbon rock" tactites and in veins
Formation of late-stage hydrothermal veins (locally sulphide-bearing)
Faulting
Fracturing

high-temperature quartz in the rhyolite and locally in the iron-poor silicated zones signifies temperatures of formation of those rock types in excess of 573° C. The wollastonite present in some of the hornfels and granulite beds suggests temperatures between 500° and 800° C.,[12] and temperatures above 573° C. are further

suggested by the presence of diopside.[13] That the temperatures prevailing during the late stages of "ribbon rock" formation were distinctly lower is shown by the occurrence of typical prismatic low-temperature quartz in the druses. Anisotropic garnet, which is common in the tactite zones, may denote temperatures below 800° C., if an analogy can be drawn from experiments made by Merwin [14] on Alaskan garnets. The very low optic angle of the adularia occurring in early-formed parts of the "ribbon rock" and locally in massive tactite would suggest heating to between 600° and 800° C.,[15] although this correlation between optical properties and physical conditions may well be open to serious question.[16]

It seems probable that the intrusive masses of rhyolite, porphyritic rhyolite, and aplitic granite must have solidified at temperatures in excess of 500° C.[17] The contact deposits on Iron Mountain are genetically associated with all three of these closely related rock types with no observable discrimination. At least a part of the massive tactite appears to have formed prior to the consolidation of nearby late-stage igneous masses, as shown, for example, by small dikes of aplite and rhyolite that break across structures and individual mineral crystals that were developed during metamorphism in large bodies of massive tactite. Thus the massive tactite seems to have been formed in part at relatively high temperatures during the period when magmatic material was still actively invading the enclosing rock. These data, together with specific information from geologically similar occurrences

[12] Eckermann, H. von: The rocks and contact minerals of Tennberg. Geol. Fören. Forh. 45: 466–537, 1923; Lindgren, Waldemar: Mineral Deposits, New York, 1933. P. 799; Knopf, Adolph: Pyrometasomatic deposits. Ore Deposits of the Western States, p. 539. A. I. M. E., New York, 1933.

[13] Eskola, P.: On contact phenomena between gneiss and limestone in western Massachusetts. Jour. Geol. 30: 285, 1922.

[14] Quoted by Wright, C. W.: Geology and ore deposits of Kasaan Peninsula, Alaska. U. S. Geol. Surv. Prof. Pap. 87: 108, 1915.

[15] Glass, J. J.: Personal communication, July, 1942; Winchell, A. N.: Elements of Optical Mineralogy, Part II, New York, 1933. P. 361.

[16] Ross, C. S.: Personal communication, April, 1943.

[17] Larsen, E. S.: The temperatures of magmas. Am. Min. 14: 81–91, 1929.

suggest that the massive tactite began to form at temperatures between 500° and 800° C., or distinctly above the critical temperature of pure water, and that the later "ribbon rock" tactite was formed at sensibly lower, gradually dwindling temperatures.

Mineral Paragenesis. The common "primary" minerals of the massive tactite are magnetite and the iron-bearing silicates andradite and hedenbergite. The pyroxene was formed after the garnet and magnetite, as recorded by Smythe.[18] Spinels, apatite, and some feldspar are minor, relatively early-formed constituents, but the sulphides are consistently later, as are the scheelite, powellite, and willemite, which clearly fill fractures in the host rock. The massive tactite also contains mineralized zones rich in fluorite, idocrase, biotite, and specularite; these are regarded as time equivalents of the "ribbon rock" bodies, which in contrast were formed directly at the expense of limestone.

Mineral paragenesis in the more complex "ribbon rock" is best interpreted on the basis of its known mode of formation. Thus the minerals in the thin, closely spaced laminæ that lie at or near the positions of fractures in the pre-existing recrystallized limestone must be relatively early, whereas those in the crystalline pods and druses are late. The arrangement of banding on most faces of "ribbon rock" is generally a reliable clue to the distribution of fractures from which the silication began (see Figs. 2, 7).

The mineral paragenesis in "ribbon rock" tactite is shown in Fig. 8. Since neither the absolute nor the relative durations of the various stages are known within satisfactory limits, intercepts at different horizontal positions are not necessarily to the same scale. The heights of the black areas along a given vertical line represent in a general way the relative amounts of the constituents being formed at a given time. Magnetite, biotite, idocrase and some specularite are relatively early minerals, whereas fluorite and much of the specularite are sensibly later. The grossularite, helvite and danalite, and quartz are relatively late, and occur almost wholly in the crystalline layers, pods, and druses.

[18] Smythe, D. D.: A contact metamorphic iron-ore deposit near Fairview, New Mexico. ECON. GEOL. 16: 415–417, 1921.

Transfer of Material. The physical and chemical nature of the solutions active in the formation of pyrometasomatic deposits can be determined with reasonable assurance in few places. Although a rough approximation of the significant chemical constituents is obtainable from a study of newly developed minerals

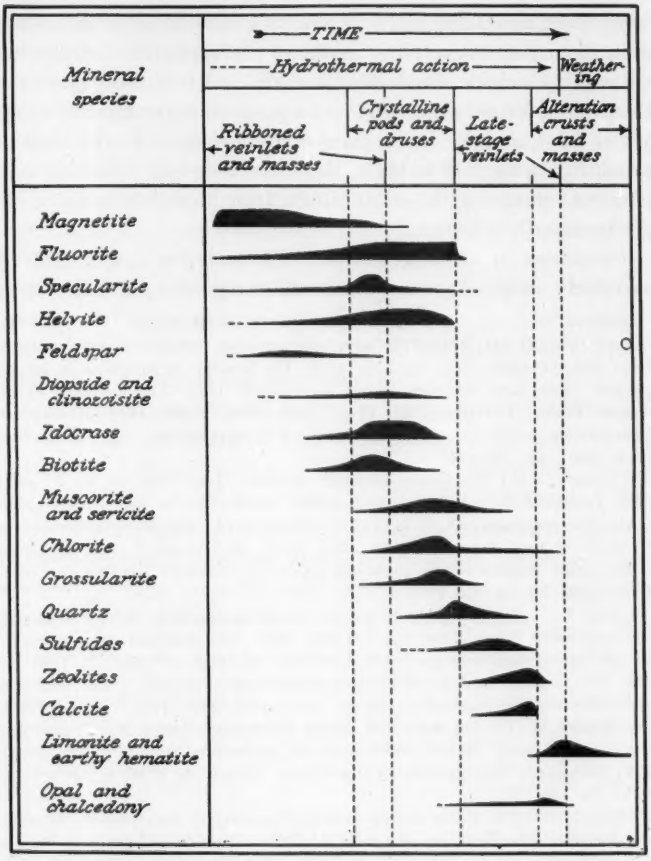


FIG. 8. Mineral paragenesis in "ribbon rock" tactite.

and the minerals that were attacked and partly or completely replaced, it is much more difficult to determine the physical conditions under which these processes were operative. In recent years the physical chemistry of magmatic differentiation and mineralization has been discussed at length by many investigators, among whom Bowen,[19] Fenner,[20] Ross,[21] Schaller,[22] and Zies [23] have been particularly active in several closely allied fields. Complete agreement concerning results of the application of physico-chemical principles, experimental work, and field observations to the problem of ore deposition and associated mineralization is not yet at hand, and for many parts of the problem definite answers are still lacking. It is plain, therefore, that the following conclusions concerning the origin of the Iron Mountain tactite rocks are necessarily tentative.

Formation of Massive Tactite. The massive tactite, with its extremely simple "primary" mineral composition (chiefly mag-

[19] Bowen, N. L.: Crystallization-differentiation in silicate liquids. Am. Jour. Sci., 4th ser. 39: 175–191, 1915; The later stages of the evolution of igneous rocks. Jour. Geol. 23, suppl. to no. 8: 1–91, 1915; The behavior of inclusions in igneous magmas. Jour. Geol. 30, supp. to no. 6: 513–570, 1922; The Evolution of the Igneous Rocks. Princeton Univ. Press, 1928; The broader story of magmatic differentiation, briefly told. Ore Deposits of the Western States. A. I. M. E., New York, 1933. Pp. 106–128.

[20] Fenner, C. N.: The Katmai magmatic province. Jour. Geol. 34, no. 7: pt. 2, 1926; Pneumatolytic processes in the formation of minerals and ores. Ore Deposits of the Western States. A. I. M. E., New York, 1933. Pp. 58–106; Review and discussion of Prof. Pap. 179 (U. S. Geol. Surv.) by Clarence S. Ross on Origin of the copper deposits of the Ducktown type in the southern Appalachian region. Econ. Geol. 30: 928–936, 1935.

[21] Ross, C. S.: Physico-chemical factors controlling magmatic differentiation and vein formation. Econ. Geol. 23: 864–886, 1928; Differentiation as a source of vein and ore-forming materials. Ore Deposits of the Western States. A. I. M. E., New York, 1933. Pp. 128–144; Origin of the copper deposits of the Ducktown type in the southern Appalachian region. U. S. Geol. Surv. Prof. Pap. 179, 1935.

[22] Schaller, W. T.: The genesis of lithium pegmatites. Am. Jour. Sci., 5th ser., 10: 269–279, 1925; Mineral replacements in pegmatites. Am. Min. 12: 59–63, 1927; Pegmatites. Ore Deposits of the Western States. A. I. M. E., New York, 1933. Pp. 144–151.

[23] Zies, E. G.: The Valley of Ten Thousand Smokes; I. The fumarolic incrustations and their bearing on ore deposition, II. The acid gases contributed to the sea during volcanic activity. Nat. Geog. Soc., Contributed Tech. Pap., Katmai ser., 1, no. 4, 1929.

netite and andradite) and its occurrence immediately adjacent to essentially contemporaneous igneous bodies of volcanic and hypabyssal rather than plutonic affinites, seems well explained as a product of deposition from iron-rich magmatic emanations that may have been incapable of transporting appreciable quantities of aluminum and the alkali earths. Their wholesale replacement of massive limestone and granulite beds suggests great penetrative power, and the high temperatures of these fluids are demonstrated by their ability to form andradite at the expense of calcium carbonate. It has already been noted that the cooling intrusive masses were overlain by a freshly fractured, relatively thin cover of sedimentary and volcanic rocks. This condition would favor the rapid escape from the magma of so-called volatile elements, which at high temperatures might pass directly into the gas phase and be subject to typical gas-phase reactions.[24] Escape of the gases could be prevented at any time by constriction or complete closure of the fracture passageways, and pressure in the underlying solutions could then be built up to the point where liquid-phase reactions would become dominant.[25]

Formation of the massive tactite, at least a part of which might be viewed as the product of gaseous transfer, has involved the deposition of large amounts of iron and the removal of carbon dioxide. Some silica also must have been introduced. How could such transfer be effected? Halogens have been regarded as the chief carriers of iron and other metals in magmatic gases because of their volatility and their proved role in fumarolic deposition, and the presence of considerable amounts of at least

[24] See, for example: Zies, E. G.: The Valley of Ten Thousand Smokes; the fumarolic incrustations and their bearing on ore deposition. Nat. Geog. Soc., Contributed Tech. Pap., Katmai ser., 1, no. 4, 1929; Fenner, C. N.: Pneumatolytic processes in the formation of minerals and ores. Ore Deposits of the Western States, A. I. M. E., New York, 1933. Pp. 58–106; Wells, F. G.: The origin of the iron ore deposits in the Bull Valley and Iron Springs districts, Utah. ECON. GEOL. 33: 498–507, 1938.

[25] See, for example: Morey, G. W.: The development of pressures in magmas as a result of crystallization. Jour. Wash. Acad. Sci. 12: 219–230, 1922; Ross, C. S.: Physico-chemical factors controlling magmatic differentiation and vein formation. ECON. GEOL. 23: 876–881, 1928.

one of these elements in the Iron Mountain deposits is shown by extremely abundant fluorite, fluor-apatite, and other fluorine-bearing minerals. Chlorine may have been present also, but the absence of scapolite and the solubility of most other chlorine compounds in aqueous solutions makes its total effect difficult to evaluate. A second mode of transfer, involving the solvent action of volatiles on non-volatile compounds at supercritical temperatures, has been pointed out by several investigators,[26] but its applications to geologic processes are imperfectly known at the present time.

That the magmatic exhalations were acid is suggested by the known acid character of volcanic gases,[27] and the contained halogen compounds and other substances indicative of relatively low critical temperatures should reduce somewhat the tendency of any extremely low-volatile solutes to raise the critical temperature of such escaping gases. Maier [28] has shown that the vapor pressures of the chlorides of Al, Fe, Zn, Pb, Ni, and some of the other common metals are high, whereas those of calcium and magnesium chlorides are very low. Beryllium chloride may well belong in the latter group, although no data on its vapor pressure appear to be available. Vapor pressures of the fluorides of these metals may be similarly related, even though each would differ in absolute value from that of the corresponding chloride. The tendency of $AlCl_3$ (and perhaps AlF_3) to hydrolyze in the presence of excess water vapor [29] probably inhibits its transportation for great distances in the gaseous phase. On the other hand, Zies [30] cites experimental evidence to show that iron can be transferred as

[26] See for example: Ingerson, Earl: Relation of critical and supercritical phenomena of solutions to geologic processes. ECON. GEOL. 29: 454–470, 1934; Geijer, Per: Processes in contact metamorphism. ECON. GEOL. 20: 688–689, 1925; Greig, J. W., Merwin, H. E., and Shepherd, E. S.: Notes on the volatile transport of silica. Am. Jour. Sci., 5th ser., 25: 71–73, 1933.

[27] Day, A. L., and Allen, E. T.: The volcanic activity and hot springs of Lassen Peak. Carnegie Inst. Wash., Pub. 360: 125, 1925.

[28] Maier, C. G.: Vapor pressure of the common metallic chlorides and a static method for high temperature. U. S. Bur. Mines, Tech. Pap. 360: 1–54, 1925.

[29] Fenner, C. N.: op. cit., p. 84, 1933.

[30] Zies, E. G.: op. cit., pp. 7–10, 1929.

chlorides in the gaseous state, despite differences in the vapor pressures of $FeCl_2$ and $FeCl_3$, and that magnetite will form when steam reacts with the two chlorides at temperatures near 550° C. The part of the Iron Mountain magnetite that formed during the early, high-temperature stages when the magma was actively invading the surrounding rock might be accounted for according to the analogous fluoride reactions. Since any magma constituent with an appreciable vapor pressure at the high temperatures prevailing during the period of invasion should be present in the gases escaping from the magma, it seems possible that sufficient quantities of ferric fluoride and the less volatile ferrous fluoride would be present to permit reactions somewhat as follows:

$$Fe_2O_3 + 6\ HF = 2\ FeF_3 + 3\ H_2O,$$
$$FeO + 2\ HF = FeF_2 + H_2O,$$
$$2FeF_3 + FeF_2 + 4\ H_2O = Fe_3O_4 + 8\ HF.$$

Since a given amount of HF will have far greater effect in driving the first two reactions to the right than the addition of an equal amount of water in driving them to the left, the iron should remain in volatile halides so long as markedly acid conditions are maintained. This assuredly would be the condition near the source magma, as well as in those channels where jacketing of carbonates by iron oxides would prevent further removal of acids from the vapors. Wherever acid could be removed through reaction with carbonates, however, formation of magnetite should proceed according to the third equation. Since all three equations are qualitative, they are merely suggested to show a reasonable mechanism for the transfer of iron and the formation of part of the magnetite on Iron Mountain that is compatible with field observations and experimental data.

Silica might be transported as the volatile fluoride, according to the equation:

$$SiO_2 + 4\ HF = SiF_4 + 2\ H_2O.$$

The HF concentration, however, would have to be high to prevent hydrolysis of the silicon tetrafluoride. Silica can also be trans-

ported with water vapor at high temperature and pressure,[31] particularly in the presence of other volatiles. Quartzite beds and chert lenses in the limestone, as well as the silicic magma itself are the most likely sources of the SiO_2.

The hot, acid solutions, with their metallic halides, water, and silica or silicon halides, presumably escaped from the magma chamber into a freshly fractured, relatively thin cover of sedimentary and volcanic rocks. Thus their pressure need not have been great. Upon reaching beds of favorable composition and structural situation, they reacted strongly with calcite and deposited magnetite and small amounts of hematite, possibly in part through much the same mechanism as that involved in the formation of fumarolic incrustations.[32] If an analogy can be drawn from calcium chloride, a substance of very low vapor pressure, calcium fluoride would be difficult to remove from such a system as a gas. Some calcium may have been used on the spot to form andradite, according to the hypothetical equations:

$$CaCO_3 + 2\,HF = CaF_2 + H_2O + CO_2,$$
$$2FeF_3 + 3CaF_2 + 3SiF_4 + 12H_2O = Ca_3Fe_2(SiO_4)_3 + 24HF.$$

It is clear, however, that a considerable amount of calcium must be removed in other ways. Gaseous transfer of this element may be accomplished in a system rich in water vapor according to Fenner,[33] who lists experimental evidence and known occurrences of calcium-rich fumarolic deposits in support of such a view. Ingerson[34] also has suggested that such a non-volatile substance might be transferable in gaseous solution with volatile solvents. It seems likely, however, that the presence of appreciable quantities of a liquid phase may best account for removal of large amounts of calcium. Thus the solutions passed outward and

[31] Greig, J. W., Merwin, H. E., and Shepherd, E. S.: op. cit., pp. 71–73, 1933.

[32] See, for example: Zambonini, F.: Mineralogia Vesuviana, p. 70, Napoli, 1910; Zies, E. G.: op. cit., pp. 5–10, 1929.

[33] Fenner, C. N.: Pneumetolytic processes in the formation of minerals and ores. Ore Deposits of the Western States. A. I. M. E., New York, 1933. Pp. 84–87.

[34] Ingerson, Earl: Relation of critical and supercritical phenomena of solutions to geologic processes. Econ. Geol. 29: 454–470, 1934.

upward following their reaction with the country rock, their temperature and acidity considerably reduced; they appear to have carried with them such constituents as lead, zinc, and manganese for deposition in cooler parts of the terrane, and probably were accompanied by condensation products rich in calcium and the halogens.

Following the escape of gaseous emanations, their subsequent deposition of magnetite and andradite, and their partial condensation, additional iron-rich vapors and subordinate accompanying liquids appear to have arisen from the underlying masses of cooling and solidifying rock. The quantitative importance of gaseous versus vapor transfer is difficult to evaluate, but the vapors probably contributed more vigorously to the formation of massive tactite; they appear to have deposited magnetite, andradite, hedenbergite, iron-rich amphibole, feldspar, scheelite, powellite, hematite, and minor amounts of other minerals. Evidently they were able to transport a variety of substances in quantity, to pervade and attack limestone on a large scale, and to carry away both calcium and carbon dioxide.

The derivation and behavior of residual magmatic solutions have been discussed clearly and at length by Bowen[35] and Ross.[36] Critical phenomena appear to have no bearing on such solutions because of the large proportion of dissolved compounds;[37] hence the persistence of a liquid phase is to be expected. This would account for the transfer of alkalies, aluminum, and much silica, in addition to the iron and other elements carried in the vapor phase. Bowen[38] has shown that this vapor phase is acid, and that its ability to attack and remove minerals is greatest after it has condensed to a liquid.

[35] Bowen, N. L.: The broader story of magmatic differentiation, briefly told. Ore Deposits of the Western States. A. I. M. E., New York, 1933. Pp. 106–128.

[36] Ross, C. S.: Physico-chemical factors controlling magmatic differentiation and vein formation. Econ Geol. 23: 864–886, 1928.

[37] Morey, G. W.: Relation of crystallization to water content and vapor pressure of water in a cooling magma. Jour. Geol. 32: 291–295, 1924; Ross, C. S.: op. cit., pp. 878–879, 1928.

[38] Bowen, N. L.: op. cit., pp. 119–125, 1933.

The massive tactite at Iron Mountain therefore appears to have been formed under vapor-phase conditions, at first from material that may well have left the magma as gases and later condensed, and subsequently from material forced from the magma as vapor-rich residual solutions. The durations of these stages, as well as the intensity of action during any period within them, were presumably controlled by the physical condition of the relatively thin, fractured cover that overlay the igneous masses. The partial or complete sealing of escape channels, alternating with periods of fracturing and fissuring would make for intermittent rising of the mineralizing solutions;[39] abundant evidence for such spasmodic action is found in the tactite masses, where each of several groups of fractures plainly was "healed" by newly-deposited tactite minerals before the succeeding group of fractures was formed. This spasmodic action appears to have been most common during the latest stages of massive tactite formation.

Formation of "Ribbon Rock." The earliest-formed constituents of the "ribbon rock" tactite differ but slightly from those of the older massive tactite, and transitional varieties of tactite actually have been observed. The relative proportions of later minerals in the "ribbon rock," however, denote certain orderly and progressive changes. Although magnetite remained dominant at first, fluorite and minerals containing aluminum, beryllium, alkalies, fluorine, and boron became more and more abundant. Biotite, helvite and danalite, and idocrase crystallized in preference to garnet, and specular hematite gradually supplanted magnetite. During the latest stages helvite and danalite, grossularite, and low-temperature quartz were formed, especially in the magnetite-poor varieties of "ribbon rock."

The great variety of elements in the "ribbon rock" tactite strongly suggests introduction of material transported chiefly in hot liquids of steadily decreasing temperature. Such hydrothermal solutions may be viewed in part as condensations of the

[39] See Burbank, W. S.: A source of heat-energy in crystallization of granodiorite magma, and some related problems of volcanism. Am. Geophys. Union, Trans., 17th Ann. Meeting, pp. 236–255, National Research Council, Washington, D. C., 1936.

vapors treated in the preceding section; the transition between the vapor-rich and hydrothermal periods appears to have been gradual, as shown by the gradual mineralogic changes during the early stages of "ribbon rock" formation. The hydrothermal solutions must have been reducing rather than oxidizing in character during the later stages, when some helvite and sulphides of iron, lead, zinc, and copper were deposited at the expense of calcite and earlier formed iron oxides.

The strikingly layered structure of the "ribbon rock" seems best interpreted as a product of diffusion and rhythmic precipitation of replacing material. Trüstedt[40] ascribed the origin of similar rock from Pitkäranta, Finland, to crustification produced by magmatic waters of rapidly changing temperature and composition. This explanation is plainly unsatisfactory for the Iron Mountain occurrences, as the layers were formed in a succession progressing away from fractures into masses of relatively unfractured carbonate rock. The arrangement of layers corresponds closely to that of iron-stained weathering rings seen in blocks of even-grained granite and silicic volcanic rocks. Laminated diffusion structures analogous to those in the Iron Mountain tactite, as well as those in the "ore arteries" from Pitkäranta,[41] Finland, and the orbicular contact-metamorphosed rock described by Knopf[42] from Alaska have been reproduced in the laboratory. The original experiments of Liesegang[43] are particularly well known.

The important role of diffusion in replacement processes has been upheld by many students of ore deposits[44] and needs no

[40] Trüstedt, O.: Die Erzlagerstätten von Pitkäranta and Ladoga-See. Bull. Comm. Geol. de Finlande, No. 19: 226, 1907.

[41] Trüstedt, O.: idem.

[42] Knopf, Adolph: Geology of the Seward Peninsula tin deposits. U. S. Geol. Surv. Bull. 358: 45–49, 1908.

[43] Liesegang, R. E.: Geologische diffusionen. Dresden and Leipzig, 1913.

[44] See, for example: Knopf, Adolph: idem, 1908; Watanabe, M.: Some problems of diffusion in the special reference to the study of ore deposits. Sci. Rept., Tohoku Imp. Univ., sec. III, vol. 2, Sendai, 1924; Whitman, A. R.: Diffusion in ore genesis. Econ. Geol. 23: 473–488, 1928; Lindgren, Waldemar: Mineral Deposits, New York, 1933. Pp. 176–177.

further comment here. The individual "ribbon rock" layers obviously could not have been controlled directly by a structure in the limestone, such as bedding, cross-lamination, or closely-spaced curving fractures, but their distribution does appear to be satisfactorily explainable as a diffusion effect. This is the conclusion reached by Knopf [45] in his study of the markedly similar Alaskan occurrences.

SUMMARY AND CONCLUSIONS.

The development of iron-rich contact rocks at Iron Mountain can be traced through a period characterized by deposition from vapors to a period during which hydrothermal solutions were dominant. The vapor stage probably was supplanted by the hydrothermal stage gradationally and with no recognizable breaks. Both vapors and liquids appear to have been acid, and reducing conditions undoubtedly existed during late stages of the hydrothermal sequence. A somewhat similar sequence appears to have obtained in the nearby Hanover district of southwestern New Mexico.[46]

The magmatic vapors, apparently well above the critical temperature of pure water, were highly pervasive and thus were able to replace great masses of carbonate rock with minor regard for fractures and other avenues of immediate access. The hydrothermal mineralization, on the other hand, possessed much less penetrative power, as demonstrated by its obvious dependence upon fractures for access to the recrystallized limestone and early silicate rocks. Magnetite was deposited from both vapors and liquids, but was itself attacked during the latest stages of hydrothermal activity, during which calcite, quartz, sulphides, and zeolites were deposited. Fluorite, aluminum-bearing silicate minerals, specularite, helvite, danalite, graphite, and pyrrhotite were laid down somewhat earlier in the hydrothermal period, and might be characterized with equal justification as hypothermal or as late-stage pyrometasomatic products. Thus the Iron Mountain

[45] Knopf, Adolph: idem, 1908.

[46] Schmitt, Harrison: The Pewabic Mine. G. S. A. Bull. 50: 812, 1939.

deposits present a rather complete gradation from an early stage of gaseous, or vapor-phase reaction to a later, typically hydrothermal stage; no typical pegmatitic stage appears to have existed, and the amount of pegmatite observed in the area is negligible.

The occurrence of beryllium in "ribbon rock," but not in noteworthy quantities in massive tactite may well indicate that little of that element could be transferred in the gaseous state. Beryllium thus would be somewhat analogous to the related elements calcium and magnesium. If this conclusion can be extrapolated to other pyrometasomatic deposits, we should not expect to find beryllium minerals as primary constituents of those rocks formed from magmatic gases or vapors, such as the "contact" iron ores in southwestern Utah.[47] Tactites of this type are mineralogically simple, and generally consist chiefly of iron oxides and iron-rich silicates. If beryllium were present in the magmatic fluids in quantities sufficient to form appreciable amounts of its compounds in the contact zones of a given deposit, such compounds should be sought for in the rocks or mineralized zones of hydrothermal origin. The occurrence of "ribbon rock" should be a useful clue, even though its consistent association with beryllium-bearing minerals is well established in but one deposit; on the other hand, there is no obvious reason why such minerals should not occur in hydrothermal bodies from which ribboned structures are absent.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
July 16, 1943.

[47] Wells, F. G.: The origin of the iron ore deposits in the Bull Valley and Iron Springs districts, Utah. ECON. GEOL. 33: 498–507, 1938.

THE BERYL–TANTALITE–CASSITERITE PEGMATITES OF PARAIBA AND RIO GRANDE DO NORTE, NORTHEASTERN BRAZIL.[1]

SANDOVAL CARNEIRO DE ALMEIDA, W. D. JOHNSTON, JR., OTHON H. LEONARDOS, AND EVARISTO PENA SCORZA.

CONTENTS.

	PAGE
Introduction	206
General geologic relations	208
Pegmatites	209
Mineralogy	210
General features	210
Beryl	217
Tantalite-columbite	218
Mine descriptions	218
Heterogeneous pegmatites in Minas Geraes	222
Origin of the pegmatites	222

INTRODUCTION.

THE pegmatite areas of Paraiba and Rio Grande do Norte are about 200 kilometers inland from João Pessoa, a city midway between Natal and Recife on the northeast coast of Brazil (Fig. 1).

They have been described by De Moraes[2] and De Souza.[3] In 1940, the Departamento Nacional da Produção Mineral opened a field office with a well-equipped chemical laboratory at Campina Grande, for the purpose of increasing the production of tantalite, columbite, beryl and possibly other pegmatite minerals. Dr. Sandoval Carneiro de Almeida has been in charge of that office

[1] Published by permission of the Director, Departamento Nacional da Produção Mineral, and the Chief of the Metals and Minerals Division, Board of Economic Warfare.

[2] De Moraes, Luciano Jacques: Cobre, estanho e outros minerais em Picui e Soledade, Paraiba do Norte. Serviço de Fomento da Produção Mineral, Bol. 28, 1938.

[3] De Souza, Henrique Capper Alves: Columbita e tantalita no Rio Grande do Norte. Divisão de Fomento da Produção Mineral, Avulso 38, 1939.

from the start. In late May and early June, 1942, through the courtesy of Dr. Glycon de Paiva, then Director of the Divisão de Fomento da Produção Mineral, Johnston, Leonardos, and Scorza

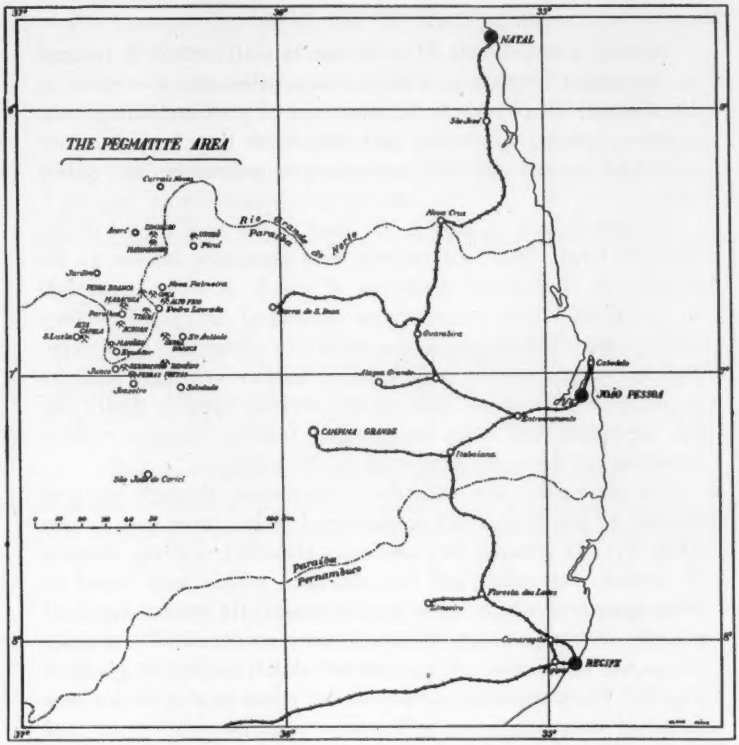


FIG. 1. Index map showing location of the pegmatite area in northeastern Brazil.

spent three weeks in the pegmatite area, driving over 2,500 kilometers, visiting more than 20 mines and mapping some of them. In early 1943, the Mining and Engineering Section of the United States Purchasing Commission of the Board of Economic War-

fare also opened an office in Campina Grande to cooperate with the Departamento Nacional da Produção Mineral in furthering the development of the area.

GENERAL GEOLOGICAL RELATIONS.

West of a littoral belt 40 to 60 km. in width which is covered by horizontal Cretaceous and Tertiary sediments, the rocks of Paraiba and Rio Grande do Norte consist of pre-Cambrian granite gneisses, schists, quartzites, and limestones that have been intruded by granites and their accompanying pegmatites and quartz veins.

The whole area, at least as far west as the central part of the State of Ceará, has been reduced to a peneplain, known as the planalto da Borborema, remnants of which, at altitudes of 500 to 550 meters, form a conspicuous element of the geomorphology of the region. In many places, mesa-like remnants of the peneplain are capped by a layer of limonite nodules, or canga, 5 meters or more in thickness. The present erosion cycle is destroying this peneplain and most topographic features express relative resistance of the rocks to erosion in this cycle.

The pegmatites are irregularly distributed through an area roughly 75 km. from north to south and 50 km. from east to west (Fig. 1). In general, they are more abundant near the contacts of granite with schist and less abundant within large areas of either granite or schist. The region presents the general aspect of a series of roof pendants of schists and quartzites within a series of granite batholiths. A generalized sketch section is given in Fig. 2. The complexity of the border phase is well shown in a series of excavations along the new road between Acary and Curraes Novos which expose many granite-schist contacts. There, a gray granite porphyry with phenocrysts of pink feldspar appears to be the freshest and youngest granite.

The pegmatites generally are more resistant to erosion than are the quartzites or schists and in consequence they stand, in many places, as walls one to ten meters in height and can readily be traced along their strikes.

PEGMATITES.

Texturally, the pegmatites can be classified roughly into two general types: (1) the homogeneous pegmatites and (2) the heterogeneous pegmatites.

The homogeneous pegmatites are generally the larger. One, west of Picui, near the Paraiba-Rio Grande do Norte boundary, is 40 meters wide and could be followed along the strike for at least 2 kilometers. It is composed of feldspar, quartz, and muscovite with an average grain size of 2 to 5 centimeters. Most of the "wall-like" dikes of the region are of the homogeneous type. This type is of no economic interest.

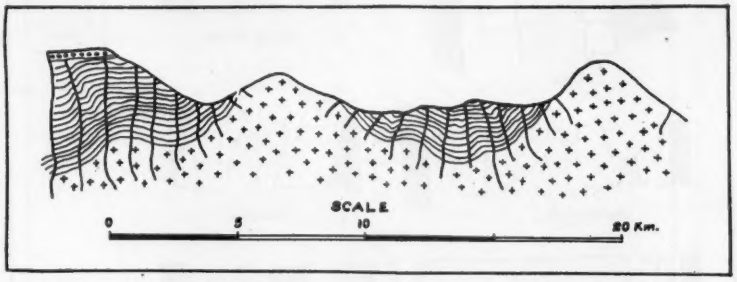


FIG. 2. Sketch showing apparent relations of pegmatites to the granite and schist.

The heterogeneous pegmatites yield beryl, tantalite-columbite, spodumene, and other minerals. They are characterized by the high degree of their internal differentiation. They are coarse grained, they commonly contain meter-long crystals of feldspar, quartz, beryl, or spodumene, and they commonly have a central core of milky or rose quartz. Figures 3 to 9 illustrate the broad geological features of this type.

The central quartz core appears to be an excellent ore guide. Because of its resistance to erosion it forms hills a few meters to more than 100 meters in height: consequently, the heterogeneous pegmatites are conspicuous topographic elements. The rose color of some of the quartz gives added prominence to the cores. Gen-

erally, the pegmatite cores can be distinguished from quartz veins, which also occur in the region, by the fact that quartz veins are more wall or fence-like with straight sides that lack the impres-

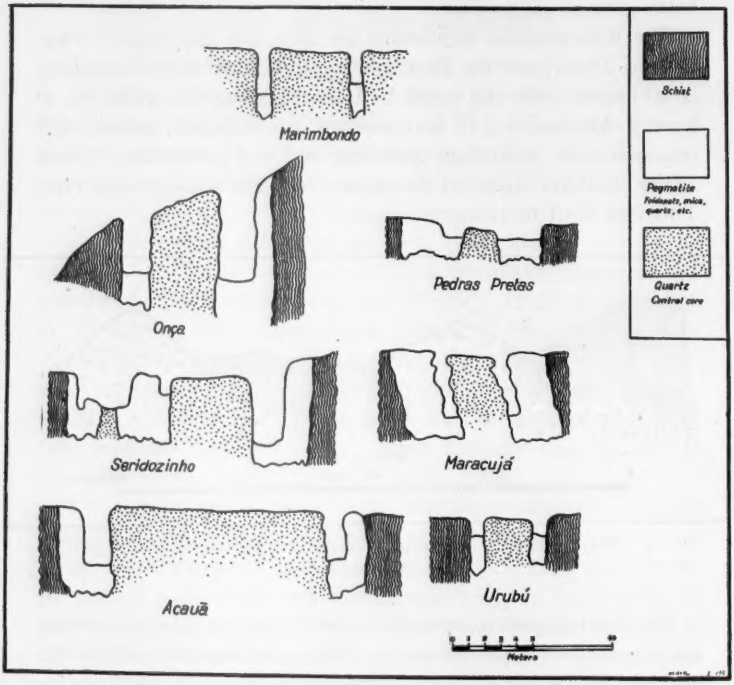


FIG. 3. Diagrammatic sections across pegmatites showing how the workings for tantalite and beryl follow the edges of the contact with the central quartz core.

sions of beryl, feldspar, or spodumene crystals usually seen in the sides of the quartz pegmatite cores.

MINERALOGY.

General Features. The heterogeneous pegmatites present certain conspicuous mineralogic and textural features:

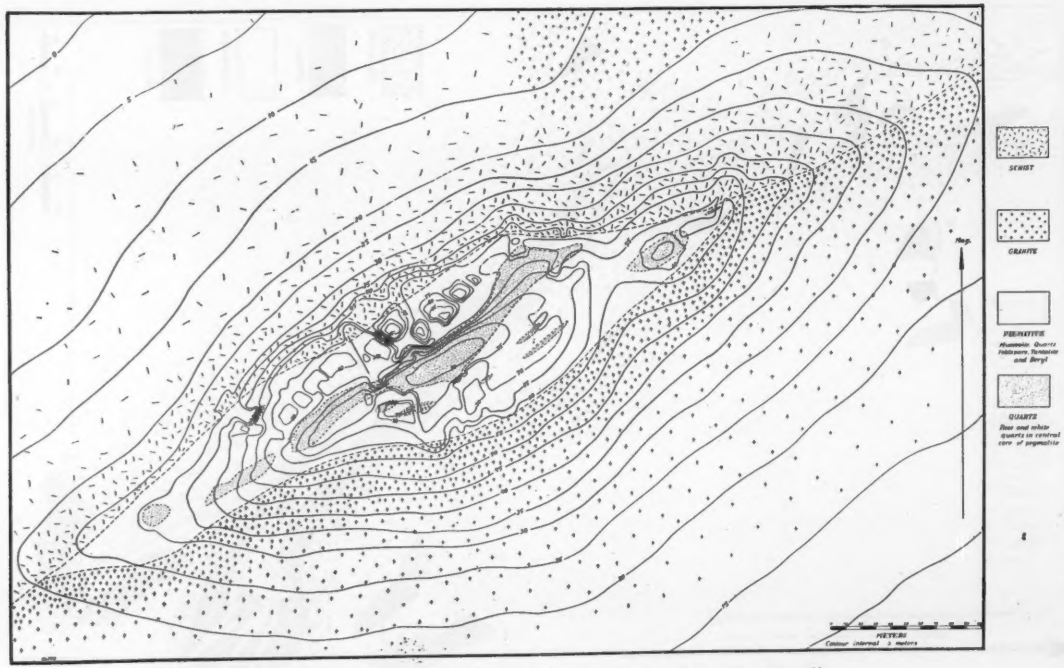


FIG. 4. Sketch map of Alto Feio mine, Pedra Lavrada, Paraiba.

FIG. 5. Sketch map of the Pedras Pretas mine, Joazeiro, Paraiba.

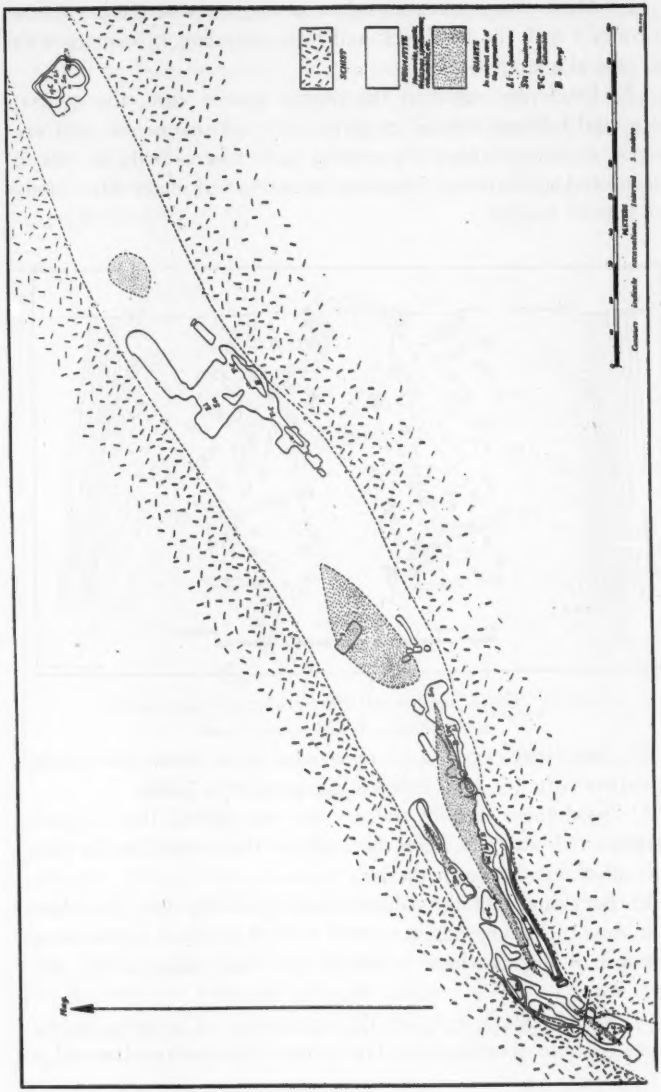


FIG. 6. Sketch map of the Seridozinho mine, Joazeiro, Paraiba.

(1) Muscovite is most abundant at the edges of the pegmatite in contact with the host rock and least abundant in contact with the central quartz core.

(2) From the edges to the central quartz core, the quartz, mica, and feldspar crystals progressively increase in size and are largest in contact with the central core where feldspar, beryl, quartz, and spodumene crystals are sometimes of meter dimensions and tons in weight.

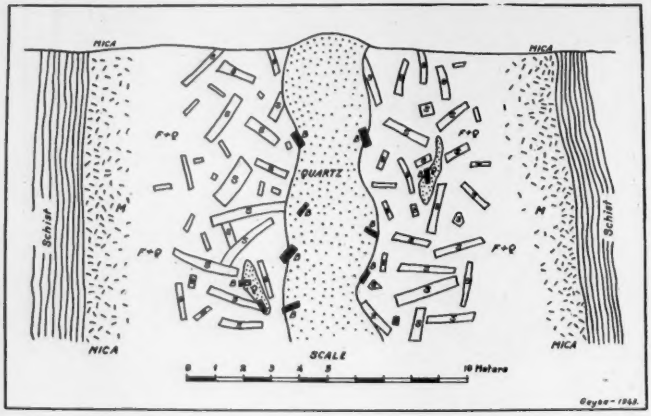


FIG. 7. Sketch section of the Seridozinho pegmatite.

(3) Cassiterite occurs with muscovite in the outer part of the pegmatites: often it is included in the muscovite books.

(4) Spodumene usually occurs in pegmatites that contain cassiterite. It extends from the walls to the central quartz core but is most abundant near the core.

(5) Beryl and tantalite-columbite are generally most abundant in the zone of big crystals in contact with the central quartz core, as shown in Fig. 3 where workings for these minerals hug the quartz core.

(6) No systematic rule for the occurrence of tantalite or columbite could be formulated as both minerals or intermediate mix-

tures of the two were found in the inner feldspar zone of most heterogeneous pegmatites.

(7) The common feldspar is microcline. Perthitic and graphic intergrowths are abundant. Albite replaces microcline along cleavages and crystal borders. This is conspicuous in many pegmatites where the microcline is salmon or pink and the albite is white. Albitization appears to be most complete in the tin-bearing pegmatites.

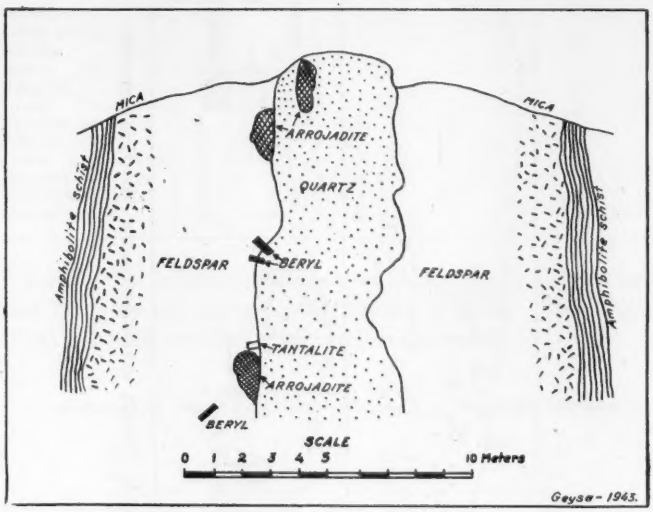


FIG. 8. Sketch section of Serra Branca.

(8) Arrojadite,[4] a manganese-iron-sodium phosphate of the wagnerite group, is an abundant mineral in some pegmatites. It occurs in the zone of big feldspars on the contact with the central quartz core.

(9) Other minerals observed are: black tourmaline; spessartite; euxenite, or a related mineral; samarskite, or a related min-

[4] Guimarães, Djalma: Arrojadita, um novo mineral do grupo da Wagnerita. Fac. Fil., Ciências e Let. Univ. São Paulo, Bol. 30: 3–16, 1942.

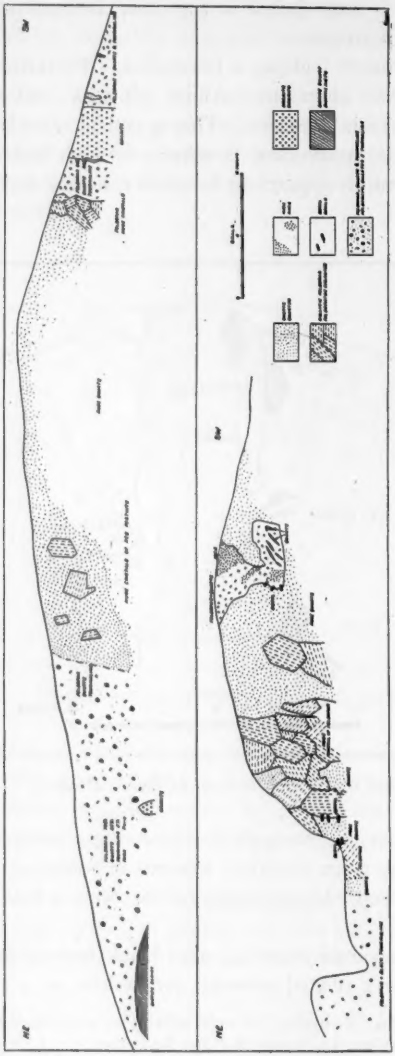


FIG. 9. Sketch section across the Alto Feio pegmatite.

eral; microlite as an alteration product of tantalite; bismutite; and citrine, smokey quartz, and bluish quartz.

The following table gives the distribution of the minerals of economic interest at the various mines described in the text:

OCCURRENCE OF MINERALS OF PRESENT ECONOMIC VALUE IN THE VARIOUS PEGMATITES.

Mine.	Beryl.	Tantalite Columbite.	Cassiterite.	Spodumene.	Bismutite.	Commercial Muscovite.
Alto Feio	X	X				
Pedras Pretas			X			
Mamões	X	X			X	
Onça	X	X			X	
Maracujá	X	X				
Acauan	X	X				
Marimbondo	X		X	X	X	
Dinheiro	X	X				
Urubú	X	X				
Malacacheta	X	X	X			X
Seridozinho	X	X	X	X		
Serra Branca	X	X	X			X

Beryl. The following two analyses of beryl from the area have been made by the Laboratorio Produção Mineral. These show 10.96 and 12.50 per cent, respectively, of glucenia.

ANALYSES OF BERYL
LABORATORY OF THE DEPARTAMENTO NACIONAL DA PRODUÇÃO MINERAL.

	a	b
BeO	10.96	12.50
SiO_2	65.32	63.75
Al_2O_3	18.61	23.05
Fe_2O_3	1.95	.48
TiO_2	traces	—
CaO	0.39	—
MgO	0.67	—
Insoluble	0.14	—
Loss on ignition	1.48	—
Total	99.53	99.78

Beryl of the area ranges in color from white to blue to green. Most is opaque but a small part is transparent. Clear crystals of light-colored aquamarine, 5 cm. in diameter and 10 cm. or more in length have been found near St. Luzia, Paraiba. The crystals range in size from a few millimeters to 60 centimeters or more.

Tantalite-Columbite. These minerals range from high-grade tantalite to high-grade columbite, with all intermediate mixtures. In general, tantalite is heavier, has a brighter luster on fresh fracture, and a better crystal form than columbite, which more commonly occurs in flat plates or "chapa." The tantalite of the area gives a seal brown streak whereas columbite gives a dark brown almost black streak. Intermediate mixtures give streaks of intermediate shades of brown.

Several dealers in the area have developed an astonishing ability to sort these minerals using the characteristics mentioned above, and can estimate the Ta_2O_5 content of a specimen to within 10 per cent.

Two standard samples prepared by the Laboratorio Produção Mineral were analyzed with the following results:

ANALYSES OF TANTALITE
(ELECTRO-METALLURGICAL CORPORATION, NEW YORK).

	Sample 1	Sample 2
Ta_2O_5	69.06	52.76
Cb_2O_5	9.15	20.90
TiO_2	2.00	2.94
FeO	12.06	10.92
MnO	1.65	3.99
SnO	1.46	2.16
ZrO_2	0.19	0.10
Total	95.57	93.77

Recent shipments of ore, sampled by Ledoux & Cia., New York, have contained 63–65 per cent Ta_2O_5, 13 per cent Cb_2O_5, 2 per cent TiO_2, and 1.6 to 2.5 per cent SnO_2.

MINE DESCRIPTIONS.

Brief descriptions of a dozen mines characteristic of the region are given in the following pages. Figures 4 to 6 are sketch maps of some of these mines, here included to give a better visual picture of the general geological relationships.

Acauan. Alto Acauan, 3 kilometers south of Parelhas, in Rio Grande do Norte, has been worked intermittently since 1938 and

has produced about 4 tons of tantalite in that time and an unknown quantity of beryl. As in most of the pegmatites in the region, the valuable minerals are found in the coarsest feldspar crystals in contact with the central quartz core.

Alto Feio. Alto Feio, approximately 1 kilometer northeast of the town of Pedra Lavrada, Paraiba, rises 80 meters above the surrounding countryside. It is characterized by its central core of bright rose quartz, the darkest rose color encountered in the region. Figure 4 is a sketch map of this mine made with plane table and tape but with barometric vertical control. In the central part of this pegmatite in contact with the quartz core are large crystals of microcline, one of which weighed approximately 11 tons, containing beryl and tantalite. The largest beryl crystal found in this mine had a diameter of 68 centimeters, was 4 meters long and weighed 4 tons. Most of the microcline is partially replaced by albite.

Dinheiro. Pedra do Dinheiro, 1 kilometer south of Carnaúbas, in Rio Grande do Norte is a spectacular wall of pegmatite 20 meters high. A small open cut on the east side of the wall has produced mainly columbite and it also has yielded some beryl.

Malacacheta. Morro do Malacacheta is a small hill ½ kilometer north of Picui, in Paraiba. It was first worked for mica and cassiterite in 1914 to 1918 but in the last year new cuts on the sides of the central quartz core have been opened and tantalite and beryl have been obtained.

Mamões. The Mamões mine, 5 kilometers northwest of Ecuador, Rio Grande do Norte, produces beryl and tantalite. The pegmatite has a width of approximately 20 meters and it outcrops for a distance of 200 meters along the strike. One cut of 30 cubic meters produced 5 tons of beryl. Both beryl and tantalite occur in great crystals of fresh feldspar weighing a ton or more. Many of the beryl crystals are large; the largest one found in this mine had a diameter of 48 inches. Workings in the more micaceous part of the pegmatite produce neither beryl nor tantalite. A parallel pegmatite, approximately 800 meters

distant, is cut by a ravine and here the feldspar is kaolinized to the bottom of the workings, 8 meters below the surface.

Maracujá. The Maracujá pegmatite, 8 kilometers northeast of Parelhas in Rio Grande do Norte, was opened in 1937 and is said to have produced 3.6 tons of tantalite and 12 tons of beryl. The largest beryl crystal weighed 360 kilograms.

Marimbondo. Alto Marimbondo, 3 kilometers southwest of Carnaúbas, Rio Grande do Norte, has been worked since 1938. In that time it has a recorded production of 11 tons of cassiterite and an unknown quantity of beryl. The cassiterite occurs most abundantly in spodumene crystals, but it is also found in the other pegmatite minerals—mica, quartz, and feldspar. Approximately 1 per cent of the pegmatite is spodumene. The complex phosphate, arrojadita, is relatively abundant here.

Onça. The Onça mine, west of Pedra Lavrada, in Paraiba, has been worked since 1937 and is one of the largest bodies of beryl- and tantalite-bearing pegmatite in the region. The pegmatite forms the backbone of a high hill, that was protected from erosion by the resistance of the central quartz core. Open cuts on both sides of this core have been opened for a distance of three hundred meters. Here the tantalite and beryl occur in the coarsest feldspar crystals and extend into the central core of quartz. One small pocket of beryl is said to have yielded 30 tons.

Pedras Pretas. The Pedras Pretas mine, north of Joazeiro and 1 to 2 kilometers east of Seridozinho mine, produces only cassiterite. The mine consists of a series of northeastward striking pegmatites in which cassiterite occurs in small crystals included in muscovite and feldspars. The older part of the mine was abandoned when the pegmatite abruptly ended. A map of the newer part, approximately 1 kilometer to the southwest, is given in Fig. 5. This part of the mine has produced about 10 tons of cassiterite.

The cassiterite-bearing mica and feldspar is crushed by hand hammers and panned in concrete water tanks installed nearby. The material is panned five or six times before it is finally discarded.

Recently the Departmento Nacional da Produção Mineral has done some trenching in the vicinity of the old mine and between the old and the new mines in search of other cassiterite-bearing pegmatites.

Seridozinho. The Seridozinho mine, near Joazeiro, Paraiba, produces cassiterite, tantalite-columbite, beryl, and spodumene. The spodumene forms very large crystals, some as much as 4 feet in length were observed. Beryl and tantalite, which occur in large crystals are picked by hand from the working face. Cassiterite, however, occurs in very small crystals, often included in mica. The cassiterite-bearing parts of the pegmatite are crushed by hammers and panned.

As shown in Fig. 6, a sketch map of this mine made with plane table and tape, but without vertical control, only about half of the outcrop area of the pegmatite has been opened for work. The map also indicates, by letter symbols, the approximate position of the richest pockets that have been found. A little chalcopyrite, partially replaced by chalcocite, was observed in the quartz body at the eastern end of the map area.

Serra Branca. Serra Branca, approximately 8 kilometers south of Pedra Lavrada, is a prominent hill which owes its existence to the central quartz core of the pegmatite. This pegmatite has yielded tantalite, beryl, and mica. Other minerals are quartz, microcline, albite, black tourmaline, and arrojadite. Arrojadite occurs in masses of several tons each in contact with the central quartz core and contains inclusions of cassiterite. The quartz in this pegmatite shows a wide range of color: white, rose, bluish, citrine, and smoky varieties were noted. The "garimpeiros" say that smoky quartz is a local guide to tantalite.

Urubú. Morro do Urubú, 3 kilometers north of Picui, in Paraiba has been worked since 1937. On either side of a central core of massive white and pale rose quartz, tantalite occurs in coarse feldspars. Beryl is relatively rare. A little arrojadite and spessartite, the latter weathering to manganese oxides, were observed.

HETEROGENEOUS PEGMATITES IN MINAS GERAES.

The other great pegmatite region in Brazil, which yields most of the mica and gem tourmalines and beryls, is in eastern Minas Geraes. In general, these dikes are narrower, less lenticular, and show less differentiation than those of Paraiba and Rio Grande do Norte. Two, however, closely resemble those of the northeast.

A dike at Gruta das Generosas;[5] near Serro in the municipality of Sabinopolis, contains a quartz core and has yielded fluorite, beryl, columbite and radioactive minerals. One beryl crystal was 2.5 meters long and 0.65 meters in diameter. The Sapucaia mine, near São Tomé in the Municipality of Cons. Pena, is a lens-like pegmatite 30 meters across with a central quartz core. Mica was mined from the outer walls and beryl containing 12 to 14 per cent BeO from the feldspar zone in contact with the core.

ORIGIN OF THE PEGMATITES.

As we have pointed out, the heterogeneous pegmatites of the area show a pronounced internal zoning, with muscovite on the outer walls and a central core of quartz. The zone of large feldspars lies between. This pattern is illustrated in the cross sections (Figs. 7, 8 and 9) and was recognized by Dr. de Moraes,[6] who gives a number of sketch sections in his 1938 report. There appears to be good evidence for a fairly definite order of primary crystallization, beginning with cassiterite and muscovite and ending with quartz.

We have no evidence from the field relations of these dikes to suppose that the present mineral assembly is the result of a series of replacements as has been suggested by Schaller[7] and others. On the other hand, the field relations appear to be best explained by a process of fissure filling, probably in an open system, wherein

[5] Leonardos, Othon H.: Tantalo, niobio, uranio, e radio no Brasil. Serviço de Fomento da Produçao Mineral, Bol. 11: 16–18, 1936.

[6] De Moraes, Luciano Jacques: loc. cit.

[7] Schaller, W. T.: Pegmatites. Ore deposits of the Western States. New York, 1933. Pp. 144–151.

the pegmatite minerals were deposited in a systematic order. The only certain replacement is that of microcline by albite. Reaction with schist walls may have contributed Al_2O_3 to the mica; in fact, secondary mica in the schist some centimeters from the pegmatite contact lends substance to this belief. The dominant mechanism, however, appears to have been one of progressive filling. We fully realize the need for microscopic studies to supplant our field observations, but these must await a happier time when there will be more leisure for pursuing such studies.

RIO DE JANEIRO, BRAZIL,
July 15, 1943.

TRACING THE DULUTH GABBRO CONTACT WITH A MAGNETOMETER.

G. M. SCHWARTZ.

ABSTRACT.

The contact at the base of the Duluth gabbro was traced for fifty miles where it is thickly covered with glacial drift. The rapidity with which this was done with a Schmidt-type vertical magnetometer suggests that such methods are useful in reconnaissance as well as in detailed work. General methods and results are summarized.

INTRODUCTION.

DETAILED mapping of outcrops in Carlton county, Minnesota, west of Duluth has led to the suggestion [1] that the slates of that area are older than the Virginia slate with which they have been correlated in recent years. This correlation in turn revived speculation concerning the rocks beneath the large covered area south of the Mesabi range and north of Cloquet where the northernmost outcrops of Thomson slate are located. The covered area is fifty miles long and the glacial drift is very thick. In a large area not a single good record exists of drill holes or water wells which have penetrated to bed rock.

During the past field season the writer, through the cooperation of the Commissioner of Iron Range Resources and of the Minnesota Geological Survey, was able to make reconnaissance magnetometer surveys over portions of this area.

Preliminary study of the problem suggested that one of the necessary tasks was to locate definitely the base of the Duluth gabbro which forms the eastern boundary of the big geologically unknown area in southern St. Louis county. The Duluth gabbro exposures have been intensively studied by N. H. Winchell and his

[1] Schwartz, G. M.: Correlation and metamorphism of the Thomson formation, Minnesota. G. S. A. Bull., 53: 1000–1020, 1942. Structures in the Thomson formation, Minnesota. ECON. GEOL. 37: 39–63, 1942.

assistants and later by F. F. Grout and to a lesser extent by other members of the Minnesota Geological Survey. The fact remained, however, that the base (western side) of the gabbro as shown on the Geological Map of Minnesota of 1932 was determined simply by connecting known areas to the north and south to form an inferred contact over a distance of about fifty miles.

It was accordingly determined to locate the contact more exactly by a series of magnetometer traverses.

METHODS.

The gabbro in common with most basic masses contains considerable amounts of magnetite and ilmenite. Portions of the mass, however, are essentially anorthosite, and in this facies the magnetite content may be low. As a rule this anorthositic facies does not form the extreme base of the intrusive, and, therefore, was not considered a likely cause of difficulty in locating the contact. Over much of the length of the assumed contact the gabbro was believed to intrude slates, but near the south end it was known from outcrops that a thin zone of basalt flows and basal Keweenawan sandstone intervened between the slates and the gabbro.

From a theoretical standpoint the problem was simple and so it proved to be. The gabbro mass as a whole dips toward Lake Superior. The dip is most pronounced at the base where probably 15 to 20 degrees is a fair average. The effect then is that of a tabular magnetic mass with its base exposed, thus giving a negative effect near, but west of the base and a pronounced positive effect when the instrument is located over the mass of the gabbro; somewhat similar to the effect illustrated by Heiland [2] for an inclined dike.

It was decided to run east-west traverses across the contact, that is, roughly at right angles to the strike of the contact. An Askania-Schmidt vertical magnetometer of the older type was used. Readings were corrected to a base station established over a slate area some distance west of the south end of the contact to be studied. Because great precision in location of the contact was

[2] Heiland, C. A.: Geophysical Exploration. New York, 1940. P. 399.

unnecessary and the anomalies were expected to be large, readings were taken at one-tenth mile intervals except where large changes made intermediate readings desirable. Readings on slate away from the contact ranged from 0 to 200 gammas, and a reading of 300 was considered high attraction. The traverses were started well west of the estimated contact where readings over slate were expected to be low and comparatively regular. This permitted location of the contact in the field with a minimum of difficulty prior to complete calculation and plotting.

Fourteen traverses of varying length were made. These were spaced at somewhat irregular intervals as shown on Figure 1. The actual spacing was determined by roads in the middle and northern portions where much of the country is wild and accessible only with difficulty. Eight days of field work by a two man party sufficed for the 14 traverses (Fig. 1) and the resulting location of the contact for a length of over 50 miles. The fact that such contacts can be traced rapidly with a relatively small expenditure of time and money is worth emphasizing.

Each traverse was calculated and plotted as soon as possible after the work was done, usually in the evening of the same day. In all cases the traverses of one day's work were completed and studied before another was made. As this work was but a part of the larger project, the traverses were not made on successive days. Figure 2 shows a composite diagram of all 14 traverses. In order to save space, some of the longer traverses are not completely shown. A few comments may serve to make the results more readily understandable.

At the south end of the area, mainly just west of the Duluth city limits, there is, as previously noted, a small tongue of Keweenawan flows and sandstone between the gabbro and slate. Actual outcrops are indicated on Figure 2.

RESULTS OF TRAVERSES.

Traverse No. 1 was made along a somewhat winding road. The values are low over the slate area, show a pronounced peak at the probable contact with basalt flows, then are irregular but gen-

erally low over the flows. The high attraction in the midst of the flow area is probably caused by a diabase dike, since one crops out a short distance to the south. The contact with gabbro shows a

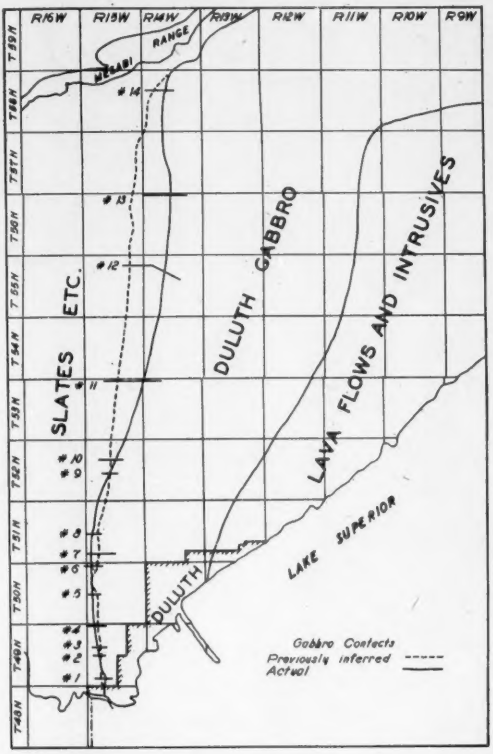


FIG. 1. Map showing location of traverses across the Duluth gabbro contact.

pronounced high followed by a sharp drop, the latter probably a result of readings over a feldspathic troctolite. This traverse showed the contact to be farther east than was inferred from scattered outcrops. The shift eastward is no doubt related to the

rock surface topography. A sharp narrow valley probably cuts out the gabbro, thus shifting the contact down the dip. This also seems true at Traverse No. 2.

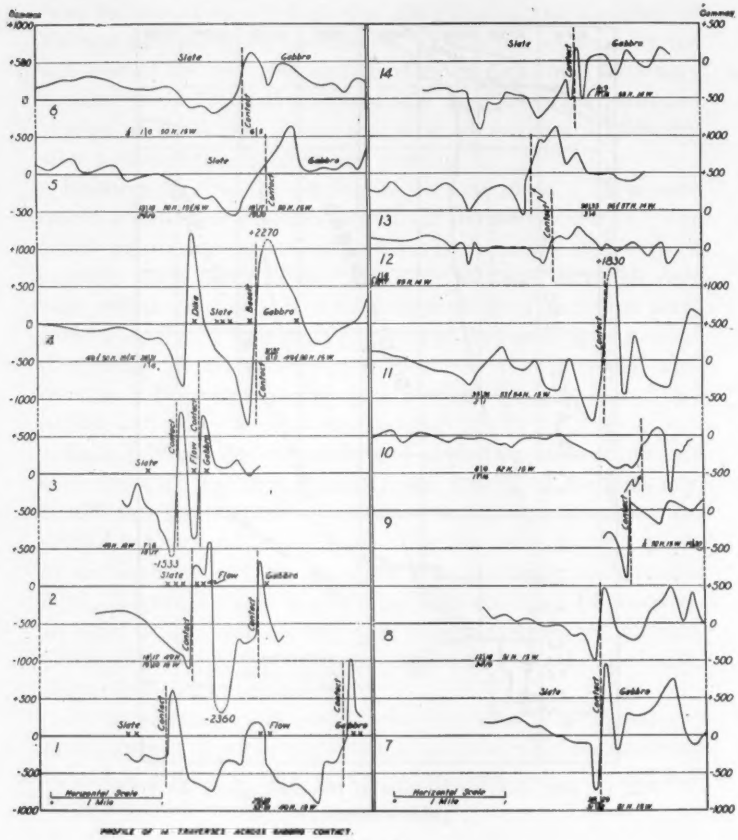


FIG. 2.

Traverse No. 2 was run over the classic locality west of Duluth where Thomson slate is well exposed within 350 feet of the overlying Keweenawan conglomerate and sandstone, with a marked

structural unconformity between. Immediately overlying the sandstone is the basal Keweenawan basalt flow. The sandstone is 20 to 70 feet thick but has little effect on the magnetic profile because it is overlain by basalt on a cliff and has little horizontal extent beyond the flow. Presumably the sandstone and slate would have about the same effect. The profile shows a characteristic normal attraction over the slate at a distance of a quarter of a mile from the contact and beyond. Near the contact of sediment with the flows is a pronounced negative effect followed abruptly by a rise of some 1,500 gammas in the attraction. As the traverse was continued eastward it passed over rocks covered by drift in a small preglacial valley and the attraction fell to an extreme low of minus 2,360 gammas as compared with positive readings of a few hundred over the gabbro. The gabbro contact is evidently a short distance east of the contact as inferred from scattered outcrops. Here, too, erosion of the gabbro probably shifted the contact eastward against a cliff of gabbro on the side of the preglacial valley or possibly so little gabbro was left that its effect was negligible.

Profile No. 3 shows the same general form as No. 2 but the crests of the flow and gabbro contacts have shifted closer together and as the outcrops indicate would be expected. This rather exact correspondence with the geology as known from outcrops seems to leave no reasonable doubt that the rise from low negative to high positive values marks the contacts.

Profile No. 4 has a very sharp crest about one-half mile west of the gabbro contact. This is probably caused by a dike, as a diabase dike in slate is well exposed along a creek about one-half mile to the south. It should be noted that, in the complete absence of outcrops, the actual gabbro contact would be in some doubt at this point. At this place the basalt flows have narrowed down to a very thin zone and give no effect distinct from the gabbro. In view of the pronounced contact metamorphism to which the flows have been subjected, this lack of distinction of a thin zone of basalt from gabbro is not surprising. As a matter of fact, it was some-

what surprising to find such a prominent change in magnetic effect at a gabbro-basalt contact as is shown by Profiles 1 to 3.

Profile No. 5 is in an area where outcrops are entirely lacking although gabbro is exposed a short way east. The glacial drift is presumably rather thick and the effect on the magnetic profile is evident. The attraction over slate is normal; falls to a low near the contact but the rise at the contact is much less abrupt than in areas where the instrument was either on or close to the rock surface. This result, it seems, is what might be expected. There is no evidence of flows affecting the profile and they are believed to have lensed out as has long been assumed from the outcrops. Profile No. 6 is so nearly like No. 5 that further remarks seem unnecessary.

Profiles 7 and 8 are similar and show a sharp increase at the contact. Inasmuch as the glacial drift is probably thick, this presents a contrast with 5 and 6 which calls for some explanation. In this connection it should be noted that the attraction over the gabbro is considerable and erratic. It is probable that the gabbro here is more highly magnetic than in the area of 5 and 6. This suggestion has some foundation in the fact that examination of outcrops of the gabbro elsewhere shows wide variation in magnetite content and farther to the northeast, extensive titaniferous magnetite deposits are well known.[8]

Traverse No. 9 was a short check traverse run because No. 10 showed a surprising trend of the contact to the east from its location in No. 8. The form seems similar to that of No. 8.

No. 10 is less decisive in its location of the contact. Presumably a great thickness of glacial drift is the cause of the flattening out of the profile. A thickness of drift of 300 feet is not unknown in this general area in Minnesota. At Taft, two miles west, 200 feet of glacial drift was penetrated in a well. A lower magnetite content in the gabbro would have the same effect, no doubt.

Traverse No. 11 shows a characteristic profile and a definite

[8] Broderick, T. M.: The relations of the titaniferous magnetites of northeastern Minnesota to the Duluth gabbro. Econ. Geol. 12: 663–696, 1917.

location of the contact. Two additional miles to the west (left) of the charted profile were traversed with decidedly regular values between 0 and 200 gammas. An equal distance over the gabbro east of the profile showed very irregular results suggesting variable amount of magnetite with perhaps a considerable concentration about one mile to the east. Lower values beyond suggest an anorthositic facies.

Traverse No. 12 was run over a distance of seven miles but only the central portion is shown. This is the least satisfactory of all the traverses in locating the contact as the anomaly is low as compared with the others. There is, however, a distinct difference in the character of the profile on the two sides of the contact as shown. To the left, variations are gradual with generally sharper rises on the west and gentle slopes to the east. Over the gabbro the readings are a series of irregular ups and downs. A thick cover of glacial deposits may well account for the results obtained.

Traverse No. 13 is a normal type of profile and leaves little doubt of the location of the contact. A considerable extention of the traverse to the west shows regular low values.

Traverse No. 14 was made west of Allen Junction where the contact was rather closely mapped by Grout and Broderick from outcrops which are abundant to the north and east.[4]

Although outcrops were not found along the road traversed, the location of the contact agrees very closely with the projection of the contact on Grout and Broderick's map and as shown on the Geologic Map of Minnesota of 1932.

DISCUSSION.

The traverses resulted in a considerable shift of the contact mainly eastward from the former maps of the contact as shown on Figure 1. The shift was fully four miles at places, but this is not excessive if the great size of the gabbro mass is considered. The more important fact is that one may now have more con-

[4] Grout, F. F., and Broderick, T. M.: The magnetite deposits of the eastern Mesabi range. Minnesota Geol. Surv. Bull. 17, plate I, 1919.

fidence in a map that shows the position of the contact as obtained from magnetometer readings.

In a broader sense the work emphasizes a characteristic of the Duluth gabbro lopolith which is deserving of comment. The base of the lopolith as traced by previous workers is well shown on the Geologic Map of Minnesota of 1932. At its southern end, south and west of Duluth, the base of the gabbro rests on a thin zone of Keweenawan flows which overlie a thin series of sandstones and conglomerates which rest unconformably on the Thomson slates. Northward this zone of lavas wedges out and the gabbro is presumably in contact with slates (probably also other rocks) northward to the Mesabi range at Allen Junction. Here the base of the gabbro turns sharply eastward and transgresses the formations so that it successively lies on Virginia slate, Biwabik iron formation, Giant's Range granite, Ely greenstone, Knife Lake slates, thence back across the Gunflint iron formation (equivalent of the Biwabik), Rove (Virginia), and finally back into Keweenawan flows. The remarkable feature of this contact is its regularity in spite of the fact that it intrudes so many different kinds of formations. So far as known there are no dikes or sills of any size projecting out from the base of the gabbro into the intruded rocks. The geophysical work in the covered area seems to agree with the observations of outcrops in this respect.

A feature of the regional magnetic effect of the gabbro which was brought out by the contact traverses in conjunction with traverses farther west, is the existence of a large area of low magnetic effect west of the base of the gabbro from Duluth to Allen Junction. This general fact was previously observed by R. H. B. Jones [5] as a result of extensive superdip work in the area. The writer believes this to be an indirect effect of the more highly magnetic gabbro to the east. The data clearly show that areas of slate five and more miles from the contact have an average value several hundred gammas higher than the same slates in a zone within five miles of the contact. The values decrease gradually to reach a minimum value within a few hundred feet of

[5] Personal communication.

the contact. There is probably a concentration of the lines of force of the earth's normal magnetic field within the gabbro mass leaving a deficiency near its base where it is underlain mainly by slates.

CONCLUSIONS.

The work seems to warrant the conclusion that a magnetometer (or superdip) can be used to trace contacts of magnetically unlike formations on a reconnaissance scale where both time and expense must be conserved. The contact of the gabbro is located in a large drift covered area north of Duluth with new and greater accuracy and has been shifted west near Duluth and east (up to four miles) in the area about 30 miles north.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINNESOTA,
May 31, 1943.

DISCUSSION AND COMMUNICATIONS

GOLD DEPOSITION.

Dear Sir: We note with considerable satisfaction the observations of William H. White.[1] At last serious thought turns along the road of practical reasoning to approach a solution to the problem of the localization of gold ore.

The author directs our attention to the possible controlling and conditioning influences of complicated stress environments and of temperature, while conceding the popular belief that the primary ore fluid was "a *dilute* aqueous solution, may not be valid in all cases." (Italics are the writer's.) Interest is centered on the question of dilute versus concentrated aqueous solution. The fact that these terms have but a comparative value seems to have been overlooked by many investigators, due to a concern with the requirements that the absolute quantities of mineral in solution should be considered to be greater than the existing data on solubilities in aqueous solution would indicate. Whatever the solution concentration, it is apparent that saturation conditions must occur under the existing temperature and pressure for precipitation (crystallization) or separation to occur. Lindgren's vague statement [2] reflects the current lack of adequate knowledge on this point. Garrels [3] and Newhouse [4] are specific to the extent of postulating from 120 to 250 grams per liter of sodium chloride.

Significant observations are:

[1] White, W. H.: The mechanism and environment of gold deposition in veins. Econ. Geol. 38: 512–532, 1943.

[2] Lindgren, Waldemar: Mineral Deposits, 4th Edit. 1933, p. 124: "The solutions . . . were often quite concentrated."

[3] Garrels, R. M.: The Mississippi valley type lead-zinc deposits and problems of mineral zoning. Econ. Geol. 36: 740, 1941.

[4] Newhouse, W. H.: The composition of vein solutions as shown by liquid inclusions in minerals. Econ. Geol. 27: 431, 1932.

1. ". . . evidence of the facile mobility of the ore fluid."
2. ". . . evidence . . . which suggests that the fluid was of sufficient density to exert an appreciable buoyancy on the earlier tourmaline crystals."
3. "The most characteristic feature of all veins is that their constituent minerals were not formed simultaneously, but in a certain sequence. The same fundamental sequence was found in all the deposits studied."

Sections of the lode at depth on the Kolar gold field show numerous examples of tourmaline crystals elongated in the apparent direction of flow of the mineralizing fluids, *i.e.* oriented in a paenevertical attitude, thus substantiating White's suggestion concerning the relative density of the depositing solutions. Tourmaline needles growing outward horizontally from the walls of veins at the Sigma mine are sometimes fractured, but their constituent sections are seldom far displaced from their original position of growth. The specific gravity of tourmaline is approximately 3.00, thus it is difficult to conceive of any strictly hydrothermal solution [5] exerting a stabilizing buoyancy on these tourmaline crystals without assuming a speed of flow that would produce extreme turbulence and certain accompanying effects that are nowhere visible. Mineral distribution in the deep-seated quartz veins is characteristic of a steady welling up of solutions within the channelways.

It should be emphasized that the observable sequence of deposition, as seen under the microscope, is the sequence of crystallization, and it should be borne in mind that the order of separation from the ore-forming fluid, depending on the nature of the latter, may not correspond exactly with the sequence of crystallization, or, in less exact terminology, of formation. The confusion of thought in regard to late gold could be eliminated if it were generally understood that an examination of thin and polished sections reveals *only* that the gold crystallized late, and does not provide the complete history of the processes of concentration and segregation, neither from the magma, nor from the mineralizing fluid.

[5] The specific gravity of a saturated saline solution of possible magmatic origin has been recorded as 1.20.

The general thesis that "great quantities of silica precipitated" from aqueous solution may be more consistently explained by the crystallization of silica from silicothermal solution, a magmative derivative in which the solvent was essentially silica.[6]

It is submitted that the so-called cataclastic structures, considered by White to have been secondary effects of "local differential stress" within a "dynamic stress environment," have been confused in their entirety with primary structures consistent with vein formation from silicothermal solutions. Features observed by White, and designated as stages in the progressive change of the quartz, may equally be no more than parallel characteristics of the original sequence of crystallization of the silica. The concept of the mobile rigidity of quartz in a metastable condition is difficult of acceptance, together with recrystallization (under pressure) without decrease of porosity.

White decides that

> . . . there is no mechanism whereby a large volume of fluid could be moved through these relatively impermeable structures against the frictional resistance of the myriads of minute, disconnected passages through which it would be obliged to pass. The alternative, that the volume of fluid must have been relatively small and of necessity rather highly concentrated, must therefore be true.

Further:

> . . . the derivation of this relatively concentrated residual ore fluid becomes difficult if the primary ore fluid is assumed to be a very dilute solution. With extraction of the common mineral constituents, the solution would become still more dilute, and derivation of the small concentrated residuum would then necessitate the separation of a large fluid fraction barren of gold and associated minerals.

The difficulties inherent in this proposition disappear if it be accepted that these deposits were mineralized through the agency of silicothermal solutions. Crystallization of the quartz from such fluids, starting as high-quartz[7] above 550° and continuing

[6] Bichan, W. J.: Nature of the ore-forming fluid. ECON. GEOL. 36: 216, 1941.

[7] Meen, V. B.: The temperature of formation of quartz and some associated minerals. Univ. of Toronto Studies, Geol. Ser. No. 38, pp. 61–68, 1935.

as low-quartz below that temperature, would give rise to still molten pools of gold, retained in this state at these relatively low temperatures by minor quantities of metallic sulphides; or of silicon, lead, zinc, copper, iron etc., if above the dissociation temperatures of the sulphides, and having sufficient dissolved or occluded sulphur for their formation at the appropriate temperatures. In regard to the probable temperatures at which these residual pools remained liquid, the "International Critical Tables" show:[8]

p. 426: gold-silicon alloys liquid at 370° C. with only 6 per cent silicon.

p. 414: gold-lead alloys liquid below 436° C. with 45 per cent or more of lead;
gold-lead alloys liquid at 370° C. with approximately 60 per cent of lead;
gold-lead alloys liquid at 220° C. with 85 per cent of lead.

Continuing with White:

> . . . this conception of the subtractive process whereby gold, present in the ore fluid since the beginning of ore deposition, finally becomes concentrated and appears as the solid late in the sequence, is inconsistent with the views of those who believe that gold is "introduced" into hitherto barren veins from some extraneous source. The writer finds no support for such views in this study of the many samples examined. The exceptional occurrence of gold in the Pamour and Broulan . . . and the absence of any possible channels of access contradict a theory based on the later introduction of gold-bearing fluid.

We are readily conversant with the effect of cold atmospheric waters on the common metallic sulphides, yet there is no appreciation of the prime difficulty of maintaining a state of stable equilibrium between freshly deposited sulphides and the currently favoured medium of transport and deposition—the hydrothermal solution.

White concludes:

[8] "International Critical Tables," Vol. II. 1927.

. . . that gold and other late minerals[9] were present during the entire period of vein formation and, as persistent fluid constituents, became progressively concentrated in the shrinking volume of fluid, appear as solid minerals only near the end of the entire sequence.

. . . within ore shoots the gold and associated sulphides are apt to occur in streaks which tend to have an en echelon arrangement almost parallel to the plane of the vein.

This writer considers quartz deposition to have taken place generally in two stages: first, a dynamic stage during which quartz and other minerals were being slowly deposited from silicothermal solutions moving through the channelways, and under the influence of falling temperature. Quartz and the minerals of early formation (the "magmatic stage" in currently popular theories of pegmatite formation) grew outward from the walls of the vein, confining the fluid residuum to smaller spaces within the vein. The relative proportions of residuum still in the fluid state depends upon the length of time during which the mineralizing fluids were traversing the channelways and assisting in the accretion of fresh crystalline material. Gold and its associates had often begun to be separated in the fluid state, mainly on account of local pressure changes. The second stage followed the eventual blocking of the channelways in the upper reaches; the silicothermal solutions came to rest, and a period of comparatively rapid crystallization ensued under static conditions, wherein the fluid was at rest. The quartz of this stage exhibits a felsitic, or pseudo-cataclastic texture, and the still molten gold association remained as the last group of constituents to crystallize, within the pseudo-cataclastic sections noted by White. Thus the "lateness" of gold is apparent, whatever may have been the stage at which it separated from the transporting fluid. The felsitic texture is only likely to appear where crystallization has been relatively rapid, *i.e.* in a comparatively cool environment. It is entirely possible that rock fracturing and movements coincident with the static phase of deposition might permit the remaining

[9] *I.e.* minerals that crystallized late, whenever their separation from the mineralizing fluid may have occurred.

fluid phases of the silicothermal solutions to migrate widely or for shorter distances, depending on the temperature of the environment. Examples of late intrusives, not yet cooled to the temperature of their host rocks at the time of gold-quartz mineralization, may be seen in the Sigma and other mines of the Canadian pre-Cambrian. Slow crystallization within a still slowly cooling environment shows no felsitic microstructures. Similarly, where the host rock of the main channelway was at an elevated temperature, one not far below that of the mineralizing solutions at the time of their introduction, felsitic textures are rare. These appear to have been the conditions obtaining at the Pamour and Broulan deposits.

Refracturing along the original lines of weakness forming the main channelways has frequently taken place during the course of crystallization of the silicothermal solutions, sometimes accompanied by the introduction of fresh fluid. The still liquid streaks of interstitial material, or newly crystallized felsitic sheet-like aggregates, formed natural lines of weakness along which movement could occur. This is the reason that native gold and sulphides may frequently be found in films or plates along planes of intermineralization movement, dislocations that took place before the metallics had fully crystallized, but after the crystallization of the bulk of the quartz.

On the Kolar gold field there is a notable decrease in the proportion of felsitic quartz aggregate over the depth range of 8,000 feet. Pseudo-cataclastic sections are rare from the lowest levels, being replaced by textures approaching the pegmatitic, but are very common at the shallower horizons. At the time of mineralization the difference of 8,000 feet appears to have accounted for a significant difference of temperature in the environment. The present difference in temperature is between 25° and 30° C.

> According to White: ". . . no mineral of this subsidiary phase of deposition [10] ever occurs in solid, aclastic quartz."

There are exceptions to this rule, admittedly rare, that have been

[10] *l.c.* late crystallization.

observed by the writer in the Kolar veins, *e.g.* pyritohedra of pyrite, and rhomb-dodecahedra of gold.

It is not at all improbable that pressure upon the veins, incident late in the static period of deposition, not only caused intermineralization shearing along felsitic lines of weakness, but also fractured the crystalline quartz aggregate and brought about a redistribution of the gold association in irregular fracture patterns and veinlets throughout the veins, but chiefly within the pseudocataclastic areas of metallic concentration.

Phenomena explainable on this basis are widespread in some deposits where pressures persisted late in the sequence of mineralization.

In accordance with the silicothermal theory here submitted, we may state that gold, present in very minor proportion in the juvenile silicothermal fluid tapped off the magma reservoir, by a rational process of fractional crystallization of non-auriferous minerals (predominantly quartz), became progressively concentrated and finally comprised one of the principal constituents of a residual alloy solution totally unlike the parent fluid. Alternatively, the separation of the alloy may, in many cases and under certain specific conditions, have commenced earlier through immiscibility. This initial separation sometimes permitted concentration of the precious metal and sulphide content towards the footwall of a channel by gravity concentration, or towards the hanging-well by flotation, or through solution flow assisted by upward-rising currents of dynamic or thermal derivation. Selective concentration of gold values can be substantiated, in some instances, by the statistical analysis of assay records of relatively simple veins, *i.e.* those wherein refracturing and consecutive tapping of the magma reservoir has been at a minimum. Further, local conditions are possible where the gold and other metallics begin to crystallize before the process of subtractive crystallization of the quartz is complete. The general occurrence of gold throughout the world is in well-defined shoots, characterized by streaks of felsitic quartz. Gold was the last mineral to crystallize, being retained at an appropriately low temperature, relative to the

magma, probably through the agency of a minute amount of silicon, up to 6 per cent, as well as quantities of lead and other metals, whether native, or in combination as sulphides. The frequent intimate association of galena and gold in the hypothermal deposits is a matter of common knowledge and has been extensively illustrated.

W. JAMES BICHAN.

SIGMA MINES, QUEBEC (temporarily on active service with the Royal Canadian Navy),
January 17, 1944.

REVIEWS*

Elements of Mineralogy. By ALEXANDER N. WINCHELL. Pp. xiii + 535; Figs. 468. Prentice-Hall, Inc., New York, 1943. Price, $5.00.

This book is designed to emphasize the fact that minerals are not fixed and simple in composition, but in most cases vary over certain limits. This emphasis is accomplished, in the section on descriptive mineralogy, in two ways: (1) many of the isomorphous groups are discussed under a group name; for example ruby silver is described, rather than pyrargyrite and proustite treated as individual species; (2) numerous graphs are presented showing the relation between chemical composition and physical properties, especially optical properties. This emphasis on variable composition of minerals is a welcome addition to a textbook of mineralogy. However, some objections can be raised over the constant reference to various isomorphous groups as being composed of mixtures of end-members, the names of which will add to the student's difficulties, and perhaps convey an erroneous impression of the true meaning of isomorphism. Also, many of the graphs pointing out the relationship between composition and optical properties will have little meaning to a beginning student.

The section of the book on crystallography is much like that found in other textbooks, but has been improved by introducing the Hermann-Mauguin symbols for the 32 crystal classes. Unfortunately, however, the modified Groth crystal class names have not been used. Part 3, Physical Mineralogy, includes, along with the usual topics such as specific gravity, a brief account of the optical properties of minerals and the use of the petrographic microscope. A section on chemical mineralogy is devoted chiefly to describing qualitative chemical tests for mineral identification. Following the section on descriptive mineralogy is one on economic mineralogy, followed in turn by determinative tables and a glossary.

GEORGE SWITZER.

Minerals in Industry. By W. R. JONES. Pp. vii + 149; Figs. 31. Penguin Books Ltd., West Drayton, Middlesex, 1943. Price, 2/.

In the preface to *Minerals in Industry* the author states that—"this small book is concerned with the minerals that supply most of the ma-

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

terials which are as essential to modern industries as food is to man." Some 55 minerals are dealt with and production figures or percentages are given for most of them. The industrial uses of the mineral products are discussed first, "in order to whet the appetite before proceeding to the assimilation of the more solid, if less palatable" description of the properties of the minerals, their mode of occurrence, and production data. It is a handy, modern source book for the geologist and, in addition, is interesting and instructive reading for the non-geologist. W. R. Jones is familiar to American geology students as the co-author of *German-English Terminology*. In England he is Professor of mining geology at the Imperial College of Science and Technology, London. He is well known in British geological circles for his research on silicosis and his work as consulting geologist.

RALPH E. DIGMAN.

Optical Crystallography. By ERNEST E. WAHLSTROM. Pp. v + 206; Figs. 209. John Wiley and Sons, Inc., New York, 1943. Price, $3.00.

The purpose of this book is to present the fundamentals of optical crystalography needed in the use of the petrographic microscope. Emphasis is laid on the fact that the petrographic microscope is not only a useful instrument to the petrographer and mineralogist, but to workers in many other fields as well. The book is designed primarily as a text in college courses in optical crystallography, but will also serve as a handbook for investigators interested in the practical application of the petrographic microscope. No determinative tables are included.

The subject matter is handled in much the same way, and in the same order, as in other books on this topic. A brief review is first given of the principles of geometrical crystallography and optics. Then follows a description of the optical behavior of isotropic, unioxial, and biaxial crystals. The most valuable feature of the book is the illustrations, which are excellent and numerous. The inclusion of mathematical formulae expressing the form of the various indicatrices and ray-velocity surfaces seems unnecessary. On the whole, however, it is an excellent book and should find wide use both as a text and as a handbook for practical investigators.

GEORGE SWITZER.

BOOKS RECEIVED.

RALPH E. DIGMAN.

Bibliography of the Geology and Mineral Resources of Montana. By C. R. WALDRON, Supervisor. Pp. 356; Pls. 3. Montana Bureau of Mines and Geology, Memoir No. 21. Butte, 1942. Price, $3.00. *The state of Montana has long been considered a classic area by all*

geologists for within this single state occurs such an abundance of geologic phenomena that all branches of the science have been represented in the investigations that have been carried on here. The nature and value of its ore deposits, the variety of its igneous and sedimentary rocks, the abundance of unusual minerals, the character of its land forms, and the occurrence of a multitude of structural features have all aided in making this state familiar to geologists all over the world. Memoir No. 21 of the Montana Bureau of Mines and Geology is as much a classic as any of the geologic features of the state. Every important reference to the geology and ore deposits of Montana have been carefully abstracted, checked, and annotated for this volume. Some two thousand references are represented. The index is divided into four units: General, Areal, Fossil and Stratigraphic, and Index of Mines and Properties. In the body of the text the articles have been arranged alphabetically by author. A correlation chart of Montana formations, together with an index map, is appended to the volume. In addition, a lexicon of Montana formations is presented in 54 pages.

American Mining Law. By A. H. RICKETTS. Pp. xxxi + 1018; Figs. 23. California Div. of Mines, Bull. 123. San Francisco, 1943. Price, $5.00. *From the state in which was developed a large part of the American mining law, have come many fine books and papers on mining law in this country. Bulletin 123 of the California Division of Mines is the fourth edition of the treatise on the laws and court decisions relating to mines in the United States. The third edition was published in 1931. At the time of his death, late in 1938, Mr. Ricketts was preparing the present more detailed and up-to-date treatise. The adjudications from the time of the death of Mr. Ricketts to the publication of this volume were prepared for the text by Wm. Metson, associate of the author. The book contains 60 chapters and 1178 sections covering every conceivable phase of the subject. The first two chapters are devoted to the definition of 235 terms and phrases of mining and oil drilling. The author has appended a section containing federal and state statutes, and a section containing 82 forms useful in mining.*

Chloride in Ground Water in the Coastal Plain of Virginia. By D. C. CEDERSTROM. Pp. 36; Figs. 5; Pls. 4. Virginia Geol. Surv., Bull. 58. University, 1943.

The Manganese Deposits of the Turtle Mountains, North Dakota. By T. A. HENDRICKS AND W. M. LAIRD. Pp. 11; Fig. 1. N. Dakota Geol. Surv., Bull. 15. Grand Forks, 1943.

The Geology of the Turtle River State Park. By WILSON M. LAIRD. Pp. 16; Figs. 7; Pls. 2. N. Dakota Geol. Surv., Bull. 16. Grand Forks, 1944.

Geology and Ground-Water Supply at Camp McCain. By G. F. BROWN AND R. W. ADAMS. Pp. 116; Pls. 11. Mississippi Geol. Surv., Bull. 55. University, 1943.

SOCIETY OF ECONOMIC GEOLOGISTS

THE TWENTY-FOURTH ANNUAL MEETING, NEW YORK CITY.

The Twenty-fourth Annual Meeting of the Society of Economic Geologists was held at the Hotel Waldorf-Astoria, New York City, February 21–24. The program was arranged in collaboration with the Mining Geology Committee and with the Industrial Minerals Division of the American Institute of Mining and Metallurgical Engineers. The technical sessions began Monday afternoon, February 21, and extended through Thursday afternoon, February 24. Sixty-three technical papers were presented by the authors in person, read for the authors, or read by title. These included descriptions of metallic and nonmetallic mineral deposits, discussions of the relation between geology and mining methods, and reports of progress in the use and search for minerals and in certain explorations of Mexico, Canada, the United States, Alaska, and South and Central America. A special session, attended by 650 persons, dealt with post-war mineral control.

The Council of the Society held a meeting on Tuesday, presided over by President W. B. Heroy. At this meeting election of the following officers and new members was confirmed:

Officers:

President for 1945	*First Vice-President for 1945*
Oscar E. Meinzer	Thomas B. Nolan

Councilors for 1944–1947

Paul Billingsley H. A. Buehler W. L. Whitehead

Regional Vice-Presidents for 1944

Alfred Brammal, *Europe*	J. A. Allan, *North America*
Balaram Sen, *Asia*	Victor Lopez, *South America*
Alexander duToit, *Africa*	Frank Stillwell, *Australia*

New Members:

George Harold Anderson, Donald Fergus Campbell, John Van Nostrand Dorr 2d, Albert Langley Fairley, Jr., Marion Dwight Harbaugh, Dwight M. Lemmon, Carl A. Moore, Wallace Everett Richmond, Lloyd Milton Scofield.

The Council also confirmed the acceptance (by a vote of the membership) of a new amendment to the By-laws, which provides that additions can be made to the official ballot if received by the Secretary within 75 days *of the mailing of the slate to the membership.* The regular reports on the work of retiring committees were accepted. Other matters discussed included: the more detailed formulation of membership requirements, the question of wartime and post-war supply of geologists (in conjunction with investigations by the Society, other cooperating socie-

ties and the War Manpower Commission), and the best procedure for continuing the Annotated Bibliography of Economic Geology.

The Annual Dinner, attended by 164 members and friends, was held on the night of February 22 at the Columbia University Club. Following the dinner came the brief Annual Business Meeting; the business transacted included the reading of the necrology and the presentation and acceptance of reports by the Secretary and Treasurer of the Society. The R. A. F. Penrose Gold Medal of the Society was then presented to Dr. W. C. Mendenhall, formerly Director of the United States Geological Survey. The medalist was introduced by Dr. D. H. McLaughlin and the presentation was made by President-Elect John M. Boutwell, following which Dr. Mendenhall accepted with a graceful speech. The address of the retiring President, Mr. W. B. Heroy, dealt with "Oil for the Future."

CHAS. H. BEHRE, JR.,
Secretary.

EDWARD BENNETT MATHEWS.

1869–1944.

Dr. Edward Bennett Mathews, emeritus professor of mineralogy and petrography at The Johns Hopkins University, died on February 4, 1944. Dr. Mathews was born in Portland, Maine, on August 6, 1869. He received the bachelor's degree at Colby College in 1891 and the honorary degree of doctor of science in 1928. He was awarded the degree of doctor of philosophy at The Johns Hopkins University in 1894 and then appointed instructor in mineralogy and petrography. In 1904 he was made professor and in 1917, chairman of the department of geology, which position he held until his retirement at the age of 70 in 1939.

Soon after the establishment of the Maryland Geological Survey in 1896, Dr. Mathews became assistant state geologist and in 1917 state geologist. Ill health compelled him to resign the latter position in 1943. His wide range of interests in many fields of knowledge, particularly in history, bibliography and cartography, was instrumental in giving to the publications of that Survey a scope beyond the customary limits of strictly geologic work. He was an important contributor to most of the volumes and either prepared or edited the many and diverse types of maps published by the Survey. He also served the State of Maryland in many other capacities, such as director of the Maryland Weather Service, executive officer of the Board of Forestry, member of the Development Commission and Water Resources Commission.

Outside of Maryland he served as chairman of the Advisory Council of the U. S. Board of Surveys and Maps, as chairman of the Division of Geology and Geography of the National Research Council, as vice president and treasurer of the 16th International Geological Congress, as president of the American Association of State Geologists, and since 1917 as treasurer of the Geological Society of America.

Dr. Mathews' wide range of interests was the result of an innate intellectual curiosity and an unselfish urge to be useful to others. He avoided public and formal exhibition of this versatility, but he was always ready and happy to share his knowledge and experiences with others in friendly informal conversation. He was an unending and never-failing source of information to his associates.

JOSEPH T. SINGEWALD, JR.

GEORGE OTIS SMITH.

1871–1944.

The associations of George Otis Smith with geological science and with the wise development of the national resources began with his first interest in geology at Colby College, which he entered in 1889, and ended with his death at his home in Sokwhegan, Maine, January 10, 1944 at the age of 72. During these 45 years geology changed from a science with few economic applications to a powerful aid to the mineral industries, and the value of the mineral production of the United States grew from 1,000 million dollars to 7,500 million. This period marked the greatest industrial development the country has known. In the development of geological science and of the mineral industries, George Otis Smith played an important and enlightened rôle.

Two associations formed the most powerful currents in his life. The earlier was his educational association with Colby College where, before his graduation in 1893, he acquired under Professor William S. Bayley the interest in geology. Smith entered Johns Hopkins, from which he received the Doctorate in 1896. In 1920 Colby College honored him with the degree of Doctor of Laws; he served the college for many years as a Trustee and in later years as Chairman of the Board of Trustees. Thus, though never by profession a teacher, his influence in educational matters was large and extended beyond his own State to the University of Chicago, where he served for a number of years as a member of the Board of Trustees.

The second long association was that with the United States Geological Survey which he joined in 1893 for summer field work even before his graduation from Hopkins. He rose rapidly to the Directorship in 1907 —resigning in 1930 when other responsibilities were thrust upon him. His early assignments were in Michigan, in Utah and in the State of Washington. He then returned to New England to work principally in Maine. Most of his field work was areal and thus broad in scope, giving full play to his fine powers of observation, his broad geologic training and interests, and his sound scientific judgment.

His appointment to the Directorship of the Survey at the age of 36 meant abandonment of geologic field research, but opened unique opportunities to influence American public policy toward wise development of mineral resources. Under his administration the Survey became an increasingly affective aid to the mineral industry and contributed effectively to the classification of the public lands, thus more adequately safeguarding the rights of the people. Official recognition of his grasp of related problems was evidenced by his appointment under the Harding administration to membership in the Coal Commission and his designation by President Hoover in 1930 as Chairman of the Federal Power Commission, from which he resigned in 1933.

George Otis Smith dedicated himself to public welfare with a devotion worthy of the best traditions of his New England forbears. His courage and high ethics had in them, however, no element of grimness even for those who differed from him, and were qualified by a fine sense of humor.

EDSON S. BASTIN.

DAVID HALE NEWLAND.

1872–1943.

David Hale Newland was born in Vienna, Oneida County, New York, April 7, 1872, and died at his home in Menands, October 18, 1943. Graduating in the classical course from Hamilton College in 1894, he continued his geological studies, first at the University of Munich, later at the University of Heidelberg, and finally at Columbia. From Hamilton College in 1933, he received the honorary degree of Doctor of Science. In 1907, he was married to Miss Milla Little of Menands, who survives, together with their two daughters and one son.

The greater part of Dr. Newland's professional life was devoted to the New York State Geological Survey, but his experience was broadened by other more temporary connections, including work in Sweden and Australia, teaching at Rensselaer Polytechnic Institute, and editorial work on the *Engineering and Mining Journal*. Leaving the State service in 1920, he did consulting and research work on gypsum and salt deposits and the metallic ores. In 1927, Dr. Newland returned to Albany to become State Geologist of New York and continued in that capacity until his retirement in 1940.

Out of years of painstaking research, which he had rare wisdom to evaluate and interpret, Dr. Newland has left a descriptive and authoritative record of Adirondack mineral deposits. His outstanding work on the magnetic iron ores of the Adirondacks, his studies of New York gypsum deposits, and his reports on the mining and quarry industries of New York State are marked equally by accuracy and professional sincerity and a balanced good judgment. Whatever Dr. Newland believed, he had the ability and the integrity to convey unmistakably. His last work, published only a few weeks before his death, was a popular guide to the Lake George region of the Adirondacks which he loved so well.

CHRIS A. HARTNAGEL.

FREDERICK GARDNER CLAPP.

1879–1944.

Frederick Gardner Clapp, consulting geologist of 50 Church Street, New York, a charter member of the Society of Economic Geologists, died suddenly while on professional work at Chickasha, Okla., February 18, 1944.

Frederick Clapp has been an outstanding figure in petroleum geology for more than a generation. His was the distinction of having established in 1908 the first permanent consultation service in the field of oil and gas geology. His success was immediate and far reaching; within a few years his prestige grew to international stature and thereafter his professional activity continued to draw him from one place to another over the earth's surface up to the very end of his long career.

In his native Boston, Clapp studied at Massachusetts Institute of Technology, where after graduation in 1901 he continued for two years as a member of the faculty. In 1908, at the end of six years on the staff of the United States Geological Survey, he established his private practice as a consulting geologist in New York. In his professional capacity his early

work included official assignments from the United States Bureau of Mines, the United States Senate and the Canadian Department of Mines. He repeatedly served as Petroleum Adviser to the Imperial Government of Iran and only recently returned from a long tour of service as a consulting expert on petroleum with the Turkish Government. His geological explorations kept him for three years in China and took him also to Australia, New Zealand, Egypt, Palestine, France, Afghanistan and the West Indies for extended periods of investigation. Yet he found time to serve as lecturer on oil geology on the faculty of Harvard in 1921 and at all times he maintained wide professional practice in Texas, Oklahoma, and practically all of the oil-producing states in his own country.

He married Helen Drew Ripley, in 1908, who, with their youngest daughter, Priscilla, continues her residence at the old home, 91 Warwick Road, Bronxville, New York. A son, Corporal Edward Gardner Clapp, is attached to the Persion Gulf Service Command in Iran. Another daughter, Clara Frances Clapp, is an Ensign in the Waves, United States Navy, Pensacola, Fla.

A prolific and scholarly writer, Clapp is the author of well over a hundred publications on oil, gas, underground water, general and economic geology, geography and archaeology. A complete bibliography of his works appears in the current volume of the Bulletin of the American Association of Petroleum Geologists. In addition to his publications, he gave of his time and interest as a fellow of five national scientific societies and as a member of nearly a score of professional societies and clubs, at home and abroad.

Frederick Clapp was a citizen of the world. His life work contributes significantly to the cause of internationalism. We have recognized values in relationships; the debt science owes industry; the debt industry owes science; but in the international theatre, governments stand deeply beholden to the Frederick Clapps of the world. If we look upon government as a social contract in the common interest, then the great void in world government can best be spanned by the friendly, helpful ministrations of that small, roving group of scientists in industry, among whom this man took his place.

WALLACE E. PRATT.

SCIENTIFIC NOTES AND NEWS

On the morning of February 22 at the joint session of the Society of Economic Geologists and the American Institute of Mining and Metallurgical Engineers (Industrial Minerals Division and Mining Geology Committee) friends of DR. G. R. MANSFIELD took the occasion to honor him publicly by a tribute presented in the presence of Dr. Mansfield and of the members of the Society and Institute. W. W. Rubey of the United States Geological Survey introduced six papers given by members of the United States Geological Survey and listed on page 80 of the January-February issue of ECONOMIC GEOLOGY (papers 3–8 by Messrs. V. T. Allen; J. C. Olson, J. M. Parker and J. J. Page; E. N. Cameron, D. M. Larrabee, A. H. McNair, and G. W. Stewart; G. T. Faust and Eugene Callaghan; C. S. Ross; and R. H. Jahns and L. A. Wright). In his tribute Mr. Rubey said:

"The six papers that follow on this program have been prepared by members of the U. S. Geological Survey in honor of their colleague, Dr. G. R. Mansfield, who was retired because of ill health on November 30, 1943. Dr. Mansfield was an active member of the Geological Survey from 1910 through 1943, for 5 years as chief of the section of nonmentalliferous deposits and for 16 years as geologist in charge of the section of areal and nonmetalliferous geology. In addition to numerous scientific papers on areal, structural and general geology, he made important contributions to knowledge of the geology of phosphates of the Rocky Mountain region, nitrate deposits of the West, greensands of New Jersey, potash of the Permian Basin, and many other nonmentalliferous mineral deposits of the United States. His wide circle of friends and professional associates join in wishing him complete recovery of health and continued success in a life of useful service."

W. E. WRATHER, director of the U. S. Geological Survey and C. N. GOULD, director of the Oklahoma Geological Survey, have been made honorary members of the A. A. P. G. by action of the executive committee "for distinguished service to the cause of petroleum geology."

L. B. WRIGHT, consulting mining geologist, has resumed individual consulting practice and is continuing his office at 206 Sansome Street, San Francisco 4, California. A. O. Hall, mining engineer, an associate since 1935, may be reached at the same address.

The Joint Annual Meeting Second War-Time Conference of the A. A. P. G., the SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS, and the SOCIETY OF EXPLORATION GEOPHYSICISTS was held in Dallas, Texas, March 21–23.

H. D. ERWIN, formerly assistant mining engineer with the U. S. Bureau of Mines, is now associated with the Union Mines Development Corp. at Grand Junction, Colorado.